Precision Daylight and Thermal Modelling of Shading Devices

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Nada te turbe, nada te espante
Dios no se muda,
La paciencia todo lo alcanza
quien a Dios tiene, nada le falta
solo Dios basta[1].

SANTA TERESA DE AVILA

This thesis is dedicated to the memory of my parents
María Nelly Pérez López and Manuel Jacinto Ajmat
they encouraged me to face life as a daily challenge,
their respectful attitude for others and endless patience
showed me a path to follow.

1. "Let nothing disturb thee; Let nothing dismay thee; All things pass; God never changes. Patience attains All that it strives for. He who has God finds he lacks nothing: God alone suffice."

Abstract

The focus of this thesis is the performance modelling of shading devices with regard to daylight illumination and thermal effect in non-domestic buildings - offices, classrooms - based on real time-varying conditions. The research is centred in quantifying the impact of external shading devices on energy demand for electric lighting, heating and cooling. The Unix-based *Radiance* lighting simulation program as the engine, and a nodal thermal model processing irradiation inputs, have been used. An adaptation of suitable calculation approaches and the development of custom-written data analysis programs have been also performed on this behalf.

The thesis begins with a literature review of current practice in modelling buildings particularly examining the daylight and thermal modelling approaches used. Daylight assessment tools and shading systems are also looked at.

A formulation of a novel hybrid dynamic lighting thermal model using the daylight coefficient approach and *Radiance*, combined with a simple thermal model has been developed. A range of external shading devices are reviewed and computer models developed in order to simulate their lighting and thermal performance. These models use, as input, real time-varying meteorological data and hence predict the internal illuminance distribution and incoming irradiation through the window-shading device system. Automated models obtaining heating and cooling loads from possible scenarios where thermal loads are linked to daylight-linked electric controls are used. The validity of the use of these modelling programs in combination is compared against an existing validated computer model.

The results of energy consumption for electric lighting, heating and cooling are organized and presented to easily compare and rate the performance of different shading options, facade orientation and climates. The results show a significant influence of shading device design upon some visual environment comfort parameters as well as upon energy consumption for electric lighting. As regards of thermal loads, it is shown that the influence of shading can be considerable if coupled with control switching strategies.

It is expected that this study and the methodologies proposed should be useful to architects, building designers and developers, particularly those requiring research based on precise modelling techniques or parametric studies. It may also be of use to developers of such as shading devices, since it can assist them in their research on improving the characteristics of their products.

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'Omnibus debitor sum'

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I declare that the content of the submission represents solely my own work.

Raul Ajmat, June 2007.

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Chapter

1 Introduction

"In the beginning, when God created the heavens and the earth, the earth was a formless wasteland, and darkness covered the abyss, while a mighty wind swept over the waters. Then God said, "Let there be light", and there was light. God saw how good the light was. God then separated the light from the darkness. God called the light "day" and the darkness he called "night"."

BOOK OF GENESIS 1, 1-5

One hundred years ago only a few countries in North America and Europe were industrialised and burning fossil fuels. These days, the whole world wishes to gain a better standard of living through increasing industrialisation. In 1900 almost all buildings were considered passive and low energy in their design. That passive design took into account local climate, culture, environment and materials [Roaf, 2000]. In architectural terms a building could be considered partly as a container and partly as contents. The container is the external envelope of the building, the contents consist of the internal spaces and their organisation to work as a whole. During the last century the world experienced enormous changes which have been reflected in the transformation of building design. Changes in the architectural form -the container- were linked to economical and technological forces and moreover to architectural trends, whereas the architectural content is linked to the primary and cultural needs and is thus less subject to change.

Following either economical, technological or trend forces, changes in the envelope aiming to improve comfort in buildings according to different human activities lead to an increase in energy consumption. Energy consumption has been maintained primarily through burning fossil fuels. It is generally accepted that carbon dioxide is the main greenhouse gas causing the climate to change, and that buildings are the main source of carbon dioxide accounting for approximately 50% of those emissions [NEF, 2005].

Energy consumption in buildings is directly related with providing a comfortable environment for living and developing indoor activities. In providing a comfortable environment for living, building envelopes play a major role in dealing with the energy coming from the natural environment. Various approaches are used to address this challenge. Some of them rely more on technological advances such as 'Advanced Envelope Systems' i.e. electrochromic glazing, building integrated photovoltaics, etc., whereas others are based on design innovations in the geometry of the envelope i.e., using external shading devices, overhangs, particular shapes for facades, etc. Both approaches and their combinations should be able to address users' preferences in terms of economic and comfort benefits.

Qualitative and quantitative research in the field of environmental psychology and building engineering respectively have investigated users' preference in non-domestic buildings (i.e. offices, schools, industries, etc.). Proximity and size of windows proved to be the reason for more stimulating, pleasant and stronger sensations, which resulted in positive effects on the state of wellbeing [Tonello, 1997, 2001]. These sensations lead to an improvement in attendance and productivity [Leslie, 2003]. Users generally prefer work places no further than two meters away from windows. Some countries based their building regulations on these findings: Holland prohibits the construction of buildings where personnel are placed more than six meters away from a window; and the environmental method of evaluation BREEAM, used in the United Kingdom, counts natural lighting as a contribution to the healthy design of buildings [CIBSE, 1987].

A conscientious design in building windows is becoming increasingly important to health, behaviour, productivity and energy savings. Therefore, the successful implementation of any of the approaches mentioned above requires careful modelling and design optimization. Of particular interest is the performance of different cases dependent on orientation and climate which are not fully taken into account by existing assessment methods when calculating lighting and thermal conditions. Ergo, the main aim of the research presented in this thesis is to bring together the precise geometric design approach with daylighting and thermal performance based on dynamic simulations.

In Chapter 2 the current practice in building modelling and shading devices characteristics are reviewed. Building modelling is focused on the precise modelling of irradiation used for overall energy consumption analysis whereas shading devices' section pays attention to a detailed description and classification of building components that can provide shading.

Chapter 3 proposes a combination of models for the calculation of lighting and thermal loads within the non-domestic sector. This chapter presents the fundamentals of the two models selected to constitute a hybrid dynamic lighting thermal model.

Chapter 4 deals with the application of the Hybrid Dynamic Lighting Thermal Model and performs a comparison against one of the validated programs in the field.

Chapter 5 addresses the implications of using different shading devices in non-domestic buildings presenting a demonstration of the hybrid model applied to external shading devices in offices for different orientation and various climates. It also addresses a methodology on how to interpret the results from a visual environment and energy consumption point of view.

Finally chapter 6 contains a discussion of the results and conclusions and suggestions for further research. The appendices include ancillary data and additional results for a wide range of situations.

Chapter

2

Energy Modelling in Non-Domestic Buildings

"And now in houses with a south aspect, the sun rays penetrate into the porticoes in winter, but in summer the path of the sun is right over our heads and above the roof, so that there is shade, if then, this is the best arrangement, we should build the south side loftier to get the winter sun and the north side lower to keep out the cold winds"

SOCRATES IN XENOPHON (C.430 TO C.354 BC)

Prior to the assessment of the energy performance of different shading devices for non-domestic buildings, it is considered necessary to review calculation methods currently in use in order to select one approach which provides sufficient precision and realism and can be adapted for this study. Also it is considered essential to have a more in-depth description of the various building components which can provide building shading and solar control. This chapter aims to meet these needs.

2.1 Preamble

Energy modelling in buildings has experienced a significant growth throughout the last five decades. Building design and operation processes can be supported by many kinds of models, including the traditional architectural scale models as well as the latest computer generated virtual buildings. From consulting engineers to architectural offices, building simulation techniques in the design process assist designers verifying their technical assumptions.

The growth in building modelling was strengthened by the need for building designers to comply with the increasing concern of regulatory bodies in promoting best practices in environmental sustainability of buildings design either through regulations or in the form of incentives to the building industry.

In North America the LEED™ (Leadership in Energy and Environmental Design) is a point based rating system. Points are earned for building attributes considered environmentally beneficial, i.e. site development, water efficiency, energy efficiency, material selection, indoor environmental quality and innovation in design.

LEED was originally developed by the U.S. Green Building Council (USGBC) to provide a recognized standard for the building industry to assess the environmental sustainability of building designs. It has now also been adapted for the specific concerns and requirements of buildings in Canada. In the Canadian version energy efficiency is relative to the Canadian Model Energy Code for Buildings [USGBC, 2006]. Furthermore, an annual report card is issued by the Canadian Energy Efficiency Alliance (CEEA), a leading non-government energy efficiency advocacy organization. The report card highlights the progress and activity of the Federal Government and provinces to reduce energy demand and consumption, while recognizing the role that efficiency and conservation have in improving Canada's competitiveness and reducing associated air pollution and greenhouse gas emissions [CEEC, 2006].

The European Union launched its Energy Performance of Building Directive in 2003. It was passed as a law by 2006 for full implementation of specific articles within a further three years. The overall objective of the directive is:

'to promote the improvement of energy performance of buildings within the community taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost effectiveness'

In the United Kingdom, European regulations are incorporated within the 'Part L' building regulations which establishes the required minimum energy performance. The most recent update of Part L was improving energy efficiency standards by 40% [DIAG, 2006].

For buildings over a thousand square meters of floor area a complete study of viability of alternative heating systems will be required. Furthermore, these buildings should have certified energy efficiency ratings as part of the information provided to any possible buyer.

2.2 Current practice in modelling buildings

The requirement of compliance with energy efficiency regulations lead to an increase of the availability and power of computer-based methods for the simulation of buildings' behaviour. Rather than an extensive survey, a comparison of the main features of the major modelling tools is made here.

DOE-2.1E: predicts the hourly energy use and energy cost of a building given hourly weather information, a building geometric and HVAC description, and utility rate structure. With DOE-2.1E, the building parameters can be determined with the aim to improve energy efficiency maintaining thermal comfort and effectiveness [Winkelmann, 1993]. It has sub programs associated to perform different simulations (LOADS, SYSTEMS, PLANT, and ECON). LOADS calculates the sensible and latent components of the hourly heating and cooling load for each temperature space, taking into account weather and building use patterns. SYSTEMS calculates the performance of air handling equipment (fans, coils, and ducts); its outputs are air flow and coil loads. PLANT calculates behaviour of boilers, chillers, cooling towers, etc. in satisfying the secondary systems heating and cooling coil loads [Crawley,2005]. ECON calculates the cost of energy. DOE 2.1E has been used extensively for more than 25 years in the US and around the world for building design studies and retrofitting analyses.

Energy Plus: Energy Plus is a software tool based on the most popular features and capabilities of BLAST[2] and DOE-2.1E. It is primarily a simulation engine where text files are used as input and output. Loads can be calculated at a user defined time step and passed to a building simulation module at the same time step. The building simulation model calculates heating and cooling system response as well as the plant electrical system response. Space temperature is accurately predicted by this integrated simulation which also provides users with a tool for the evaluation of realistic system controls, moisture in building elements, radiant heating and cooling systems and inter zone air flow.

Energy Plus has two basic components - a heat and mass balance simulation module and a building systems simulation module. The building systems simulation handles communication between the heat balance engine and various HVAC modules (coils, boilers, chillers, pumps, fans, etc.). The heat and mass balance modules manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager.

For daylighting calculations Energy Plus is based on three popular windows and daylighting models from DOE-2.1E -fenestration performance based on WINDOW 5 calculations, daylighting using the split-flux inter-reflection

2. BLAST (Building System Laboratory 1999) sponsored by the U.S. Department of Defence (DOD), has its origins in the NBSLD program developed at the U.S. National Bureau of Standards in the early 1970s. It uses a zone heat balance approach while DOE-2 uses a room weighting factor. [Crawley et al, 2004]

model and anisotropic sky models. It allows to calculate interior daylighting illuminance, glare from windows and glare and electric controls (on/off, stepped, continuous dimming). In addition, the module DElight has been integrated using a radiosity inter reflection method.

ESP-r: is a dynamic thermal simulation program which was first introduced more than 25 years ago and has been in continuous development since then. Primarily, it is used in research to simulate the thermal performance of buildings under different climate conditions, heat gains, occupancy schemes, building construction and heating systems. However, its use has became increasingly popular as a consulting tool amongst architects, engineers, and also as an engine for other simulation environments. ESP-r carries out an explicit energy balance in each zone of the building and in each surface of each zone. It also works in connection with other programs, i.e. *Radiance*, and it allows interaction with supply and demand matching tools. ESP-r's structure contains three main applications: a project manager, a simulator and a results analysis, which can communicate with each other as well as complimentary applications and data bases via information flows and controls specified.

ECOTECT: It is characterised by its interactive and visual features linking 3D modelling with performance tools: thermal, energy, lighting, shading, acoustics. It can perform an analysis of the whole building, allowing designers to make decisions based on visual and numeric results. The results can be mapped on the building's surfaces giving a clear idea of the improvements made through design. One of the main features of ECOTECT is its capability to interact with other analysis engines, in addition to its own calculations, it can import and export from Radiance, Energy Plus, ESP-r and others. Amongst the latest software it is very popular within the architect and designers' community and it is also gaining popularity within a wider group of environmental designers.

IES-VE-: Is a Dynamic Model which has been tested using ASHRAE standards and qualifies - as a dynamic model - in the CIBSE system of model classification in Guide A [CIBSE, 2006]. It offers an environment for the evaluation of buildings and systems design in a very detailed way allowing them to be improved with regard to comfort criteria and energy use. It is a dynamic thermal simulation tool based on first-principles mathematical modelling of building heat transfer process. A 3-D geometric representation is the central node to which all related data is applied. IES-VE is essentially a package of software solutions for a number of different calculations: air and radiant temperatures, comfort statistics, natural ventilation, HVAC, shading and solar penetration, building dynamics and thermal mass. It can produce comfort statistics, energy use and carbon emissions estimates.

Simple Nodal Model -SNM- It was named here as Simple Nodal Model - SNM, for brevity - is a simplified thermal response model based on a calculation program known as EXCALIBUR (Exeter Calculation in Building Thermal Response) developed by Crabb, Murdoch and Penman, at the Department of Physics, University of Exeter, UK [Crabb et al., 1987]. The original version was design as a single zone one, later adaptations to be applied to cases with several rooms or partitions were made by Hanby [Hanby et al., 1995].

The aim of analising different design alternatives at low cost in terms of execution time was the driving criteria to decide amongst them. Some of the analysed models can perform very detailed thermal simulations, however considerations taken in account were related with their ability to produce long term information quickly after making design changes. For this piece of work the latter was conclusive to decide that the Simple Nodal Model was a suitable one as significant reductions in execution time while maintaining an acceptable level of accuracy was reported [Hanby et al., 1995].

2.3 Irradiation modelling

Irradiation modelling is one of the key issues for thermal and natural lighting calculations. Since the work presented in this thesis focuses on the simulation of external shading devices, irradiation modelling through transparent surfaces is particularly relevant. This section addresses irradiation modelling in its visible portion, daylight, and in its consequences within the built environment, thermal performance.

Some of the software packages which use irradiation modelling for the thermal calculations make comparable assumptions, for example that windows are not thermally coupled with external shading devices. They only take into account the solar radiation which is partially unobstructed by the shading device. The problem to solve is then transformed into a purely geometrical one. Solar radiation consists of two main components: direct and diffuse. In order to obtain the solar radiation impinging on the transparent surface, the direct solar radiation is assumed to be uniform. It is estimated as the product of the fraction of the window area which is sunlit and the direct solar radiation. The diffuse solar radiation is reduced by a fraction calculated as the view factor between the transparent system and the sky. No correction is made to take into account the reflection of the radiation on the shading device itself, nor the splitting of diffuse radiation into typical fractions reflected from the ground and coming from the sky. Moreover, it is common practice in daylight calculations that only variations in altitude are considered instead of three dimensional calculations [Rodriguez, E. et al., 1988]. All these considerations for the calculation of the radiation coming through the window-shading device system make the solution for the complex process taking place in transparent materials a simpler, although less accurate. The thermal modelling of buildings is then, carried out at a high level of precision, accounting for most of the thermal exchanges between different surfaces and for the interaction with occupants. In contrast, irradiance and daylight quantities, which are particularly important for windows performance evaluation, are predicted using less precise approximations [Ajmat et al., 2005].

2.3.1 Thermal modelling

Most thermal modelling programmes spend much of their efforts on simulating detailed heat transfer phenomena in order to accurately predict the overall thermal balance of buildings. Those interactions are grouped into 'gains' and 'losses' in order to analyse how design could possibly influence them. These gains and losses pass through 'opaque' and 'transparent' components of buildings. The definition of opaque or transparent is related to the ability of the element to let visible irradiation pass through. For surfaces considered transparent, the design of windows and shading devices usually plays an important role regarding the 'gains' they affect, such as irradiation coming from the sun, the sky and surrounding surfaces before it reaches the interior where it is perceived partly as heat and partly as daylight.

Carefully designed windows-shading device systems can, in principle, be used to modulate daylight admittance and to reduce the use of electric lighting while meeting the occupants' lighting quality and quantity requirements.

2.3.2 Daylight modelling

Modelling is a widely used method for the assessment of daylight in buildings, either for qualitative (e.g. patterns of solar penetration) or quantitative (internal illuminance) purposes. Numerous modelling tools for determining the amount of daylight passing through building envelopes into indoor spaces have been developed to date. For non-domestic buildings the internal illuminance is usually evaluated at workplane height, i.e. 0.75 - 0.80 m, where most tasks are considered to take place [Glaser et al., 2002]. Some of the tools are based on the traditional concept of the Daylight Factor (DF)[3]. The advantage of the DF approach lies in the significant simplification of the method used to estimate daylight levels. Although Daylight Factors are practical for a quick evaluation of the effects of window design, they use the CIE overcast sky, i.e. ignore the real conditions of variability that the resource 'daylight' has in its nature even under overcast sky conditions. Daylight Factors do not take into consideration the effects of direct sun or any other sky alternative and are thus invariant to the building's orientation.

When a detailed estimate of the energy balance of a room is required, or when the luminance distribution within a daylit room must be known in detail, the conventional methods of calculation are insufficiently precise. Hence, methods aiming to be more computational efficient and accurate in their predictions are based on the Daylight Coefficient (DC)[4] approach [Tregenza et al., 1983].

The advantage of the Daylight Coefficient approach lie in the possibilities of using realistic skies for simulations, i.e. it can predict the daylight performance of an internal space under variable sky and sun conditions. Additionally, this approach has a low cost of computing the internal illuminance once the DCs have been calculated for a particular geometry [Littlefair, 1992]. Therefore, this technique provides a more efficient way to evaluate the daylighting performance of a building under more realistic sky and sun conditions [Mardaljevic, 2000a].

Lighting conditions (direct and indirect light from the sun and the sky) as well as building characteristics have been simulated through various different techniques. Amongst the wide range of the simulation techniques

3. This factor is calculated as a ratio between: the illuminance at a given point on a given plane within a room (usually the *work plane*), and the simultaneous exterior illuminance on a horizontal plane under standard overcast sky conditions. Usually the DF is expressed as a percentage.

4. The DC approach considers two main factors as the major influence on the amount of daylight that falls on a surface in a room: the luminance of the sky, and the form and materials of the surfaces. As the sky luminance can vary independently from one angle to another, the DC approach is based on the contribution of a large number of 'pieces' (or patches) into which the sky is divided, to the internal illuminance. Each one of these patches is considered on its own and calculated separately. Afterwards, the total illuminance is obtained by summing the contribution of all these patches.

a simple classification based on the means used to carry out the imitation work of the building and lighting conditions is presented here to include scale and computing modelling.

Scale models

For many years scale models provided a very useful way to predict daylight performance in buildings. Scale models have been used either with an artificial overcast sky, with lamps simulating the sun position, or even directly outdoors under 'real' weather conditions. However, these representations of 'real conditions' cannot be considered sufficient for the purposes of accurate predictions: either they are counting the irradiation coming from a sky but no sun (artificial overcast sky) or sun but no sky (lamps). Outdoors tests can account for some of the variations while the experiment takes place but not for a sky luminance distribution widely representative of local conditions throughout an entire year for example.

Arbitrary sun and sky conditions have been modelled lately with artificial domes. These domes have a hemi-spherical arrangement of a large number of independently controlled lamps and can reproduce almost any sky luminance distribution. However, only a model placed at the origin gives back precise results, otherwise there is a parallax error [Mardaljevic, 2000b]. It has been also proven, that assessing daylight performance through physical building models has a limitation in the representation of real conditions. This was brought up by analysing simple scale models and real buildings simultaneously under real skies. Dimensional accuracy and photometric properties of surfaces were identified as the key factors regarding average relative discrepancies between scale model and real buildings, reaching up to +60% to +105% [Thanachareonkit, A., 2005]. Furthermore, an error band of at least 20% was found even when more care than usual was taken when building the scale model [Cannon-Brookes, 1997].

Computer modelling

Quantitative computer aided daylight modelling of buildings requires an accurate prediction of the time varying internal illuminance distribution, i.e. accounting for temporal events such as sky luminance changes. As mentioned before, the Daylight Coefficient approach is one of the methods which allows to perform simulations under variable sun and sky conditions at low computational costs. The DC approach has been implemented within different modelling tools:

ESP-r: has been described previously in Section 2.2.

DAYSIM: combines the Daylight Coefficient approach and the backward ray-tracing process from *Radiance*. Indoor illuminances can be calculated in short-time-steps and linked with user occupancy data and blind control strategy in order to predict the annual electricity lighting use.

XDAPS: The (eXtensible DAylighting Prediction System) was developed by Mardaljevic at De Montfort University, Leicester, UK [Mardaljevic, 2000b]. It is a system for the calculation of daylight coefficients and illuminance based on the *Radiance* lighting simulation system. Therefore, its formulation was partly directed by the engine program's own algorithms and requires the computing of three Daylight Coefficient Matrices using programs custom-written in IDL (Interactive Data Language) and Unix C-shell. Validation under real sky conditions using the BRE-IMDP[5] dataset *XDAPS* proved to be highly accurate. The study compared illuminance predictions with measurements taken in full size office spaces under real sky conditions. The system used model sky luminance patterns based directly on measured sky brightness distributions reducing uncertainties in model representation greatly. Most of the variations expected in a UK Test Reference Year (TRY) were considered to be contained in them. The validation process can be

5. A total of 754 simultaneous measurements of internal illuminance and sky luminance were collated by Mardaljevic into a dataset. These collated measurements were from a sky monitoring study carried out at the Building Research Establishment (BRE) during 1992 and 1993 as part of the BRE contribution to the International Daylighting Measuring Programme (IDMP) [Mardaljevic, 2000c]

found in details in some of Mardaljevic's publications [Mardaljevic, 2000b], [Mardaljevic, 2001].

This technique has also been used for modelling the performance of advanced envelope systems [Nabil, 2002] leading to the establishment of new paradigm of the assessment of daylight in buildings [Nabil et al., 2005].

2.3.3 Daylight Assessment tools

It has always been particularly difficult to evaluate daylight performance since the variability of the resource (natural light) and uniformity on a "work plane" are parameters that cannot be easily managed by the designer.

Daylight Factor

Throughout more than fifty years the Daylight Factor (DF) has been used as a quick indicator for the internal distribution of daylight across the work plane. Furthermore, it is still widely used for quantitative predictions even when reliable evidence has been reported against it. However, it is well known that the DF concept cannot account for the variability of the source or the orientation of the building as mentioned in Chapter 2 (see Section 2.3.2). For this research it has been decided to work with more realistic skies -Daylight Coefficient approach- in order to predict more accurately energy consumption due to electric lighting.

Daylight Autonomy

Another assessment tool for daylight in buildings is the Daylight Autonomy (DA) concept, which measures how often a minimum work plane illuminance threshold of 500 lux can be maintained by means of natural light. [Reinhart, C., 2002]

Limitations of the Daylight Autonomy concept lie in the fact that it ascribes no relevance to daylight illuminance values below 500 lux which have potential to displace all or part of the electric lighting. Also, there is no estimation of the amount by which the threshold illuminance was exceeded at any particular instant, disregarding the identified association of high illuminances levels with occupants discomfort [Nabil et al., 2006].

The interpretation of climate-based analyses of daylight illuminance levels that are originated on hourly meteorological data for a full year, requires the application of a more comprehensive concept for metrics. This concept may include an adequate range of illuminance levels in working environments.

Useful Daylight Illuminance

Useful Daylight Illuminance (UDI) [Nabil, 2002] is a relatively new metric for the assessment of daylighting performance in non-domestic buildings.

UDI is defined as the annual occurrence of illuminance levels across the work plane that are within a range considered 'useful' by occupants. It is usually expressed as a percentage of the annual working hours and preserves much of the interpretive simplicity of the conventional Daylight Factor approach. Therefore a simple characterization of a space can be made with reasonable accuracy [Nabil, 2002].

The range of illuminance levels considered 'useful' (for UDI concept) is based on surveys of reports of occupants' preferences and behaviour in daylit offices with user operated shading devices. It has been determined that visual performance of the human eye varies significantly amongst individuals, i.e. it can perform satisfactorily within a large range of lighting conditions. Even when criteria for visual comfort diverge widely between authors, proximity and size of windows proved to be the reasons for more stimulating, pleasant and stronger users' sensations. This resulted in positive effects on the state of wellbeing, improving attendance and productivity of non-domestic buildings' users. [Tonello, 1997 and 2001] [Reinhart, C., 2004]

Numerous lighting codes recommend to use a design illuminance level of 500 lux for work places in offices (i.e. CIE, Commission Internationale d'leclairage, CIBSE in UK, IESNA in North America, IRAM in Argentina, etc.).

Ergo, artificial electric lighting is regularly designed to deliver 500 lux evenly distributed across the workplane. If the availability of daylight is enough, then artificial lighting may be reduced or switched off by either users or automated control devices.

Field studies in Cambridge, UK, monitoring occupants' light exposure in two different buildings over a normal working week, found a dramatic difference between the occupants of a daylit building receiving illuminance greater than 2000 lux and another artificially lit where occupants rarely receive more than 100 lux [Cawthorne, A. 1994]. A more common observation is that people will tolerate much lower illuminance levels of daylight than artificial light, particularly in diminishing conditions at the end of the day, such as continuing to read newspapers at levels as low as 50 lux [Baker, N., 2000].

Experiments carried out at Lawrence Berkeley National Laboratory, USA, allowing office workers to control manually the blade angles of mechanical venetian blinds and to vary the level of electric lighting showed that resulting illuminances were between 840-2146 lux in the morning and between 782 and 1278 lux in the afternoon. This revealed occupants' preference for higher light levels than those set by the automated control system (510-700 lux). These experiments concluded that most of the occupants preferred greater illuminance levels from both daylight and electric lighting for their office space, even though they could see well enough to perform their tasks using the designer's recommended light levels [Vine et al., 1998].

Based in occupants' preferences the limits of the range for UDIs were established by Nabil as follows [Nabil, A., 2002]:

- Less than 100 lux is considered insufficient as a source of illumination or to contribute to artificial lighting.
- Between 100 and 500 lux is considered effective either as the sole source of illumination or in conjunction with artificial lighting.

- Between 500 and 2000 lux is often perceived either as desirable or at least tolerable.
- Above 2000 lux is likely to produce visual or thermal discomfort or both.

Following the survey of daylight metrics, it is observed that:

There is a significant difference between climate-based modelling like Daylight Autonomy and UDI than the idealised sky luminance pattern of the Daylight Factor approach.

UDI provides a more informative and comprehensive assessment of daylight conditions than that which can be gained from Daylight Autonomy.

UDI gives a higher quality insight into the spatio temporal dynamics of daylight illumination, particularly it is found useful for the evaluation of shading devices, indicating their effect on high levels of illumination that are associated with discomfort and solar gains.

2.4 Shading systems in buildings

As stated previously the main purpose of this research is to provide a tool able to assess and predict shading devices' energy performance in order to make design more energy efficient. Shading devices should be carefully designed and orientated in relation to the fenestration to maximise shading during summer months and heat gain during the winter season.

The primary admittance for solar radiation in a building is the fenestration system. Fenestration systems may influence building energy use through a number of mechanisms, i.e. thermal heat transfer (U-factor), solar heat gain, air infiltration and daylight. It has been reported that fenestration shaded from the outside can reduce solar heat gain by as much as 80% [ASHRAE, 2001].

Building shading components are traditionally used as a passive design strategy to reduce the solar (heat and light) gain. However some shading devices like louvres or overhangs are ideal also for active design strategies, i.e. integration of photovoltaic cells [BPsolar, 2002] or solar collectors [Palmero-Marrero, 2005]. The type of material and surface properties surrounding the glazing area affect the heat transfer across the glass by releasing or re-radiating the stored heat in as long wave radiation to the atmosphere and surrounding surfaces.

Within the non-domestic sector knowledge about the influence of windows and their positive effects on the state of wellbeing is challenging design precepts. There is an increasing interest in catering to both physiological (thermal and visual comfort) and psychological (view or contact outdoors) needs. In this respect, the design of shading devices has been an undervalued field for quite a long time.

The use of shading devices throughout the last decades has not been developed as expected after the 70s' oil crisis, when the awareness of energy efficiency increased strongly worldwide. A renewed concern towards carbon emissions, climate change and sustainable design positioned the use of daylighting as an urgent issue again particularly in non-domestic buildings.

Knowledge about the influence of daylighting on health, behaviour [Kuller, 1981] and productivity [Leslie, 2003] together with energy savings, demands the optimization of shading devices' design, which is becoming an important topic of study. The creation of decision support tools to facilitate design of daylit spaces have been strongly encouraged in the late 1990s by: facilitating the exploration of virtual spaces; catering for quality visual environments (quantity and quality of lighting); accounting for a wide range of sun and sky conditions for the evaluation of daylighting and the impact on thermal loads [Selkowitz, 1998].

2.5 Shading systems: description and classification

Shading can be provided by many different means: natural landscape features (mature trees or hedge rows), urban landscape features (other buildings) or by building elements as part of the facade. This work focuses on building shading devices.

Building shading and solar control can be provided using various building components, they can be classified in relationship with their relative position to the window to include:

- Exterior elements.
- The glazing system itself (low shading coefficient -SC- glass).
- Intermediate horizontal elements (related to the glazing system).
- Interior control devices.

Each one of these shading elements should be considered when trying to face the challenge of integrated approaches of building design aiming to fulfil at the same time visual and ergonomic, as well as thermal and energetic requirements [Gugliermetti, 2006].

Effective shading devices' design depends on many considerations comprising: solar orientation, local climate, geometric site constraints, indoor activities or specific visual tasks, building appearance, etc.

The simulation system developed in the present study (see Chapter 3) concentrates on most of these issues leaving the building appearance to the designer's decision. However, shading devices can affect significantly building appearance, the earlier in the design process they are considered, the more likely they are to be aesthetically integrated with the entire architectural project [WBDG, 2006].

This thesis aims to support designers in the analysis of alternatives by including most of the issues mentioned previously, without compromising flexibility to test different aesthetic parameters, i.e. shape, materials, colours, brightness, layout, etc.

2.5.1 External Shading Devices

Shading supplied by external devices can provide different possibilities to cater for heat protection and/or daylight regulation subject to design options. The selection should depend on the expected performance, considerations of durability and maintenance as well as the desired external appearance. The following section gives an overview of the most common types of external shading designs:

- *Overhangs* work better when the sun is high, they are therefore most effective at low latitudes and on the facade facing the sun at midday (South or North depending on the hemisphere). During summer time they can protect windows from direct sun rays whereas in winter they would allow them to pass through. For many non-domestic buildings, where glare is an issue, an overhang might need extra shading to control low altitude winter sun [Littlefair, 1999].
- *Canopies and awnings* can give a little extra advantage to an overhang. However, if they are movable, extra light can be allowed in when overcast skies are present and more protection can be achieved during the winter season. Parametric studies of the impact of awnings on energy use reported large energy savings when using a simple seasonal awning [Dubois, 2001].
- *Louvres* in this study parallel slats sloping outwards outside the window, with small dimensions and proportional separation in between are referred to as '*louvres*' [Collins, 1997]. They can be positioned vertically or horizontally and be fixed or movable depending on the orientation of the building. Vertical louvres serve well towards East and West and near these orientations. They can shade the whole window and when movable they can open up in different directions according to the sun's position. Vertical louvres can perform properly when protection and glare control is needed for low sun angles.

- *Vertical fins* cut out sunlight from fixed directions. They are used to protect an East or West orientation from midday sun, and similarly for windows facing North in the northern hemisphere during the first and last hours of daylight (and vice versa for southern hemisphere).
- *Deep window reveal* can provide the same kind of protection as vertical fins or a horizontal overhang provided the glazing is close to the inside of the wall.
- *Shutters* in the form of traditional shutters or in the form of roller shutters in low latitude countries provide very good solar control but they obstruct the view. They can be helpful within the domestic sector, protecting unoccupied rooms during the day. If the material of the shutters is well insulated then they can also reduce heat loss at night.
- *Eggcrates* are combinations of horizontal and vertical devices. They are efficient in hot climates because of the high ratio of shade.

2.5.2 Glazing

The glazing system itself can be considered as a shading system, particularly when using glasses with low shading coefficients. The variety of glazing types available in the market is significant. Options include:

- *Tinted glazing* is often referred to as "heat absorbing". The body of the glass is tinted and blocks direct solar heat by absorbing it in the glass itself. It therefore causes the temperature of the glass to rise.
- Another type of glazing often referred to as 'tinted' is *reflective glazing* which has semi transparent metallic coatings applied to its surface. This results in reduced solar gains and cooling loads but compromised daylight availability.
- *Low emissivity glazing*, or spectrally selective glazing, is designed to allow a higher level of visible irradiation to pass through. It therefore admits more daylight than conventional tinted glass. This glazing type is better at keeping heat in than having any impact on solar heat gain.

- *Windows film.* Like tinted glass and low emissivity glazing these films can reject heat in summer but have losses of heat in winter and low daylight admittance. Where UV radiation is an issue, i.e. museums, art galleries or windows exposing fabrics, paintings or drawings at risk of fading, UV films can be used to block ultraviolet radiation.
- *Diffusing glazing.* Materials used for this type of glazing can be considered between simple and complex glazing. Direct sun falling on it results in scattered daylight. Such windows can prevent glare on work planes. However, they obscure the view and, depending on the position of the sun, can become a source of glare themselves.
- *Prismatic glazing.* The principle behind prismatic glazing is refraction. An array of ridges or little triangular prisms reflect and refract sunlight, redirecting it to specified angles. Depending on the array of prisms they can alternatively exclude direct sun or admit diffuse light only. They are usually placed at the top of the window to avoid obstruction of the view and glare at eye level.
- *'Smart' glazings* is applied to glazing with the ability of controlling properties responding to seasonal or environmental conditions. They include:

  Electrochromic and liquid crystal glazing which can be reversibly switched to transparent coloured state when a small electric current is applied.

  Photographic glass. Light transmission across the glazing diminishes as the light falling on it increases. However, they can also darken on a cold sunny day.

  Thermochromic glass: When heat warms it up the glazing reacts by increasing its resistance to heat transmission.

  Amongst these 'smart' glazings the electrochromic is the one which can change its optical properties in a more flexible way.

2.5.3 Intermediate shading elements

In this work are referred to as 'intermediate' elements those particular devices that are incorporated to the window, do not configure independent external or internal elements and work mainly as horizontal reflectors, i.e. light shelves, mid-pane devices.

- *Light shelves:* A light shelf is a horizontal device which provides shade below it and can reflect light from its upper surface towards the interior ceiling. Light-shelves can be internal, external or 'half way' between the interior and exterior of the window. Normally light-shelves are located above the eye level, i.e. over 1.80 meters high from the floor level, dividing the window into two parts: the 'view window' below the shelf and the 'clerestory window' above it. The more carefully designed the light shelf is to reflect light onto the ceiling (through location, tilt, reflectance, etc.), the better its performance on improving daylight distribution within the room. Suggestions of reasonable performance have been made for an external light-shelf of depth equal to its own height above the desk level [Littlefair, 1995]. It is evident that the performance can vary significantly for different orientations and latitudes. Recommendations for using additional shading in the case of West and East facades in high latitudes, have been made, whereas for low latitudes and the facade facing midday sun's position, the light-shelf can be designed to block direct sun [Littlefair, 1999].
- *Mid-pane devices* can include blinds or fixed louvre systems in the air gap of double windows, double skin facades, etc. They usually consist of micro venetian blinds operated by electric motors or magnets. An advantage compared with an internal blind system is that heat absorbed by the blind is not inside the room and therefore can be emitted outside. Fixed louvres with curved slat profiles have been designed according with the latitude to reflect sunlight back in summer and admit it and redirected in winter and autumn.

2.5.4 Interior shading devices

These types of shading devices limit the glare resulting from solar radiation. The main advantage is that occupants can adjust them to their needs. However due to their position inside the glazing pane, the heat coming from the sun enters this space and remains indoors, i.e. solar gains are not avoided. Internal shading devices include roller blinds, roman blinds plated blinds of fabric but the most widely used devices of this type within the non-domestic sector are venetian blinds and vertical louvre blinds.

- *Venetian blinds* are usually horizontal. In small sizes venetian blinds can offer privacy and glare control allowing the possibility of adjustment to restrict either sunlight or sky glare. Variations in design can include translucent, perforated and reflective slats. All these designs transmit some extra light. Daylight redirection works if the slats' curvature faces the rays from the sun and the blinds are not fully closed.
- *Vertical louvre blinds.* Amongst fabric blinds, vertical louvres are the most popular ones. They normally hang in strips from a rail attached to the ceiling over the window. These blinds cater better for East and West orientations as the sun beams are at an oblique angle to the glazing. The possibility of tilting the louvres to keep out the sun while keeping a view and incoming daylight still exists with manual controls. For the usual tasks of non-domestic buildings and particularly with offices, where computer screens are common, recommendations exist to use light colour close-weave blinds with daylight transmittance below 10% [Littlefair, 1999].

2.5.5 Summary

In this thesis the focus is in studying non-domestic buildings (i.e., classrooms and offices). After the consideration of a wide range of shading and solar control elements, a decision was made to select those fixed elements that do not receive always an in-depth analysis in lighting-thermal modelling and are not simply managed by users. The possibilities of analysing the lighting and thermal effects of using external shading devices in non-domestic buildings are addressed in the next section.

2.6 Combined Lighting-Thermal modelling of shading devices

Solar radiation coming from the sun and the sky can be one of the major energy fluxes in building simulation. It influences both, thermal and daylighting performance of buildings, particularly in cases where windows play a very important role as part of the facade design. In order to perform reliable lighting and thermal predictions, it is necessary to determine a sky radiance pattern based on measured weather data (i. e. the radiance pattern of a clear sky is highly anisotropic and cannot be represented by any overcast or uniform distribution).

The consideration of reflected solar radiation coming from the sun and the sky can be significant in the estimation of the entrant solar radiation, particularly if the incidence of all the surfaces surrounding the window is taken into account (i. e. other buildings, the ground, sills of the building itself and shading devices).

Studies performed on window reveals have proven that an important part of the entrant radiation through a window can be diffuse radiation coming either from the sky or from reflection from surrounding surfaces (Figure 2-1) [Mardaljevic et al, 2006].

Normally this is a point where most of the simulation programs are weaker: using approximations in the presence of shading. A significant difference may appear when calculating the total solar irradiation coming through the window. It is common practice to calculate the line of sight obstruction of the sun explicitly for one day of the month but rarely for every hour of the year. For diffuse radiation a variety of approximations are employed, i. e. skies may be assumed to be uniform and the radiance of obstructions is

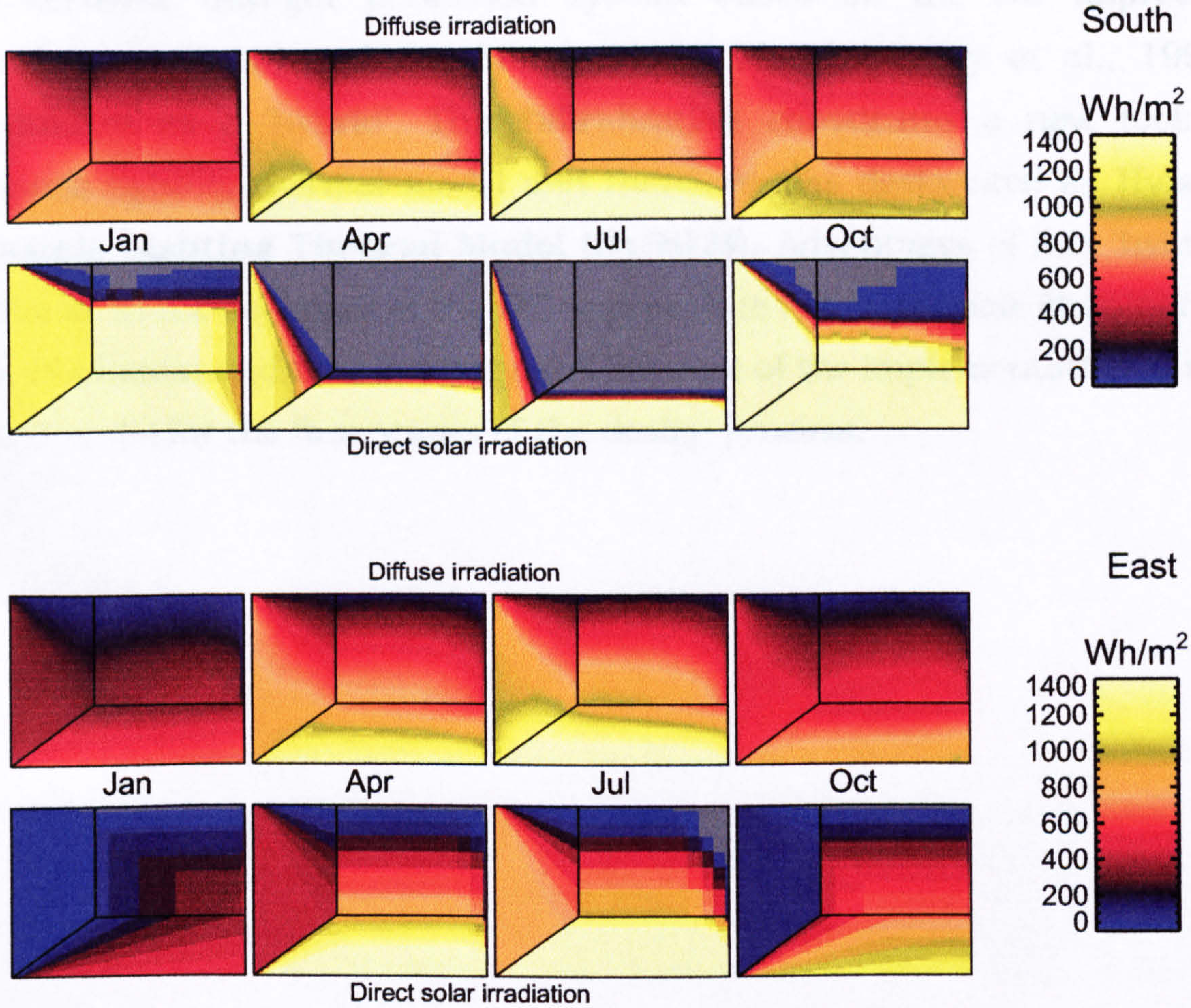


Figure 2-1 From [Mardaljevic et al., 2006]

estimated from rule of thumb algorithms rather than explicitly modelled by ray casting. Such assumptions may result in significant uncertainties.

On the other hand, when daylight contributions are calculated in thermal programs, the magnitude and distribution of internal daylight is generally determined from algorithmic approximations rather than the explicit modelling of multiple reflections. Some programs only offer the Daylight Factor as a basis for the estimation of the daylighting potential of a space. A comparison of the accuracy of the different approaches has been highlighted previously (Section 2.3). Therefore, it can be stated that daylight algorithms in thermal programs are suspected of uncertainties.

The suspected uncertainties in the thermal modelling treatment of solar gain with shading and daylight in general lead to propose the novel approach outlined in chapter 3. This approach consists of a combination of the accurate daylight prediction system based on the DC approach [Mardaljevic, 2000] and the Simple Nodal Model [Hanby et al., 1995] formulated as a 'hybrid'. This hibridization constitutes a new tool: a dynamic lighting-thermal model and therefore was designated as **Hybrid Dynamic Lighting Thermal Model (HyDiLM)**. Advantages of this 'hybrid' model lie in the accuracy of the DC approach to estimate solar illuminance and irradiation and the simplicity and low cost of the implementation of the nodal model for the first stages of the design process.

Chapter

3

The Hybrid Dynamic Lighting-Thermal Model I: Fundamentals

"Also marvellous in a room is the light that comes through the windows of that room and belongs to the room.The sun does not realise how wonderful it is until after a room is made. A man's creation, the making of the room, is nothing short of a miracle. Just think that a man can claim a slice of the sun"

LOUIS KAHN FROM 'BETWEEN SILENCE AND LIGHT'

(1979).

Irradiation modelling which aims to calculate energy loads due to thermal process and daylighting, is an intricate issue.

There are a number of questions regarding the accuracy of the treatment of solar gain for thermal and daylighting modelling in non domestic buildings with shading devices in existing models, as outlined in chapter 2. This lead to the development of a novel modelling technique.

The new model is formulated as a 'hybrid' of two preceding techniques. The daylight estimation has been entrusted to the prediction system based in Mardaljevic's implementation of the DC approach [Mardaljevic, 2000], while the thermal modelling is based on the accuracy of inputs coming from the lighting simulations and processed through a Simple Nodal Model [Crabb et al., 1987] and [Hanby et al., 1995]. The aim of providing a versatile tool for the first stages of the design process can be ensured since the proposed technique, allows an 'a priori' evaluation of shading devices' design with reasonable precision. Chapter 3 presents the foundations on which this new technique is based while Chapter 4 shows its application and a comparison to a validated tool.

3.1 Building a Hybrid Dynamic Lighting-Thermal Model

Figure 3-1 summarizes the idea of the hybrid dynamic lighting-thermal model developed in depth throughout Chapter 3. The lighting simulation provides time-varying illuminance and irradiation values based on standard climate data. The irradiation values are used as input for a dynamic thermal response model which calculates heating and cooling loads.

Daylight Simulation is based on a prediction system developed by Mardaljevic at De Montfort University, Leicester, UK. The tool was originally presented as *XDAPS* (eXtensible DAylighting Prediction System) [Mardaljevic, 2000b]. The system calculates daylight coefficients and illuminance values using the *Radiance* lighting simulation system. Originally Mardaljevic's formulation was developed with the intention of testing the accuracy of the luminances derived through the DC approach

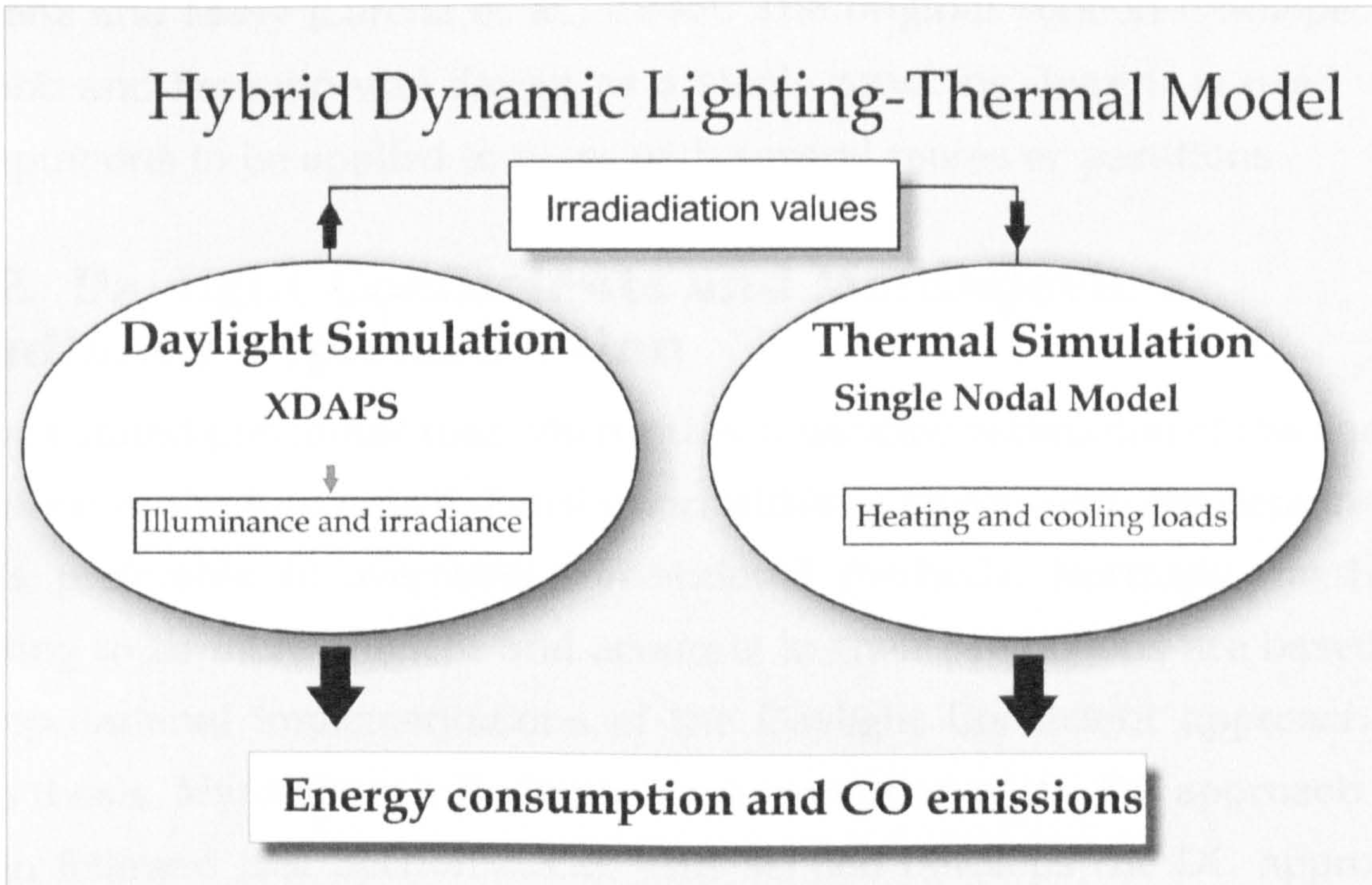


Figure 3-1 Resources used for HyDiLM

against the BRE-IMDP[6] validation data set. The validation under real sky conditions (using the BRE-IMDP dataset) proved to be highly accurate. Outputs for this program are illuminance and irradiance values. Illuminance values allow predictions of electric lighting usage based upon weather data and users' patterns of preferences and behaviour. On the other hand, irradiance values are used as part of the inputs for thermal simulations.

The model chosen in this thesis to perform **Thermal Simulations** is a simplified thermal network simulation model. The Simple Nodal Model -SNM- is based on a calculation program known as EXCALIBUR (Exeter Calculation in Building Thermal Response) developed by Crabb, Murdoch and Penman, at the Department of Physics, University of Exeter, UK [Crabb

6. International Daylight Measurement Programme -IDMP- implemented by the CIE (Commision Internationale de l'Eclairage) to collect long-duration time-series data for a range of daylight parameters. The Building Research Establishment -BRE- in Garston, UK, was one of the 'research class' stations which registered sky brightness distribution. [Mardaljevic, 2000]

et al., 1987]. The Exeter model follows the scheme of Laret [Laret, 1980] and Lorenz and Masy [Lorenz et al., 1985]. The original version developed by Crabb and Penman was design as a single zone one, here it is used with adaptations to be applied to cases with several rooms or partitions.

3.2 Daylight Coefficients and Mardaljevic's *Radiance* implementation

It was stated previously that when either a detailed estimation of the energy balance or the luminance distribution within a daylit room are demanded, it is preferable to overcome conventional methods. Normally, methods aiming to be more efficient and accurate in their predictions are based on computational implementations of the Daylight Coefficient approach. In this thesis, Mardaljevic's *Radiance* implementation of the DC approach has been followed (see Section 2.3.2). This section develops the DC approach itself and Mardaljevic's implementation in detail.

3.2.1 The Daylight Coefficient approach

The DC approach considers two main factors as the major influence on the amount of daylight that falls on a surface in a room: the luminance of the sky, and the form and materials of the surfaces. As the sky luminance can vary independently from one angle to another, the DC approach is based on the contribution of a large number of 'pieces' (or patches), into which the sky is divided, to the internal illuminance.

Each one of these patches is defined as a small element of the sky at altitude γ and azimuth α and considered on its own and calculated separately (Figure 3-2). Afterwards, the total illuminance is obtained by summing the contribution of all these small elements. Furthermore, the illuminance in the room is not equally sensitive to changes in the brightness of different parts of the sky. For instance, the portion of visible sky through the window from any of the points in the room influences the internal light more than other parts of the sky which contribute only by reflection [Tregenza et al., 1983].

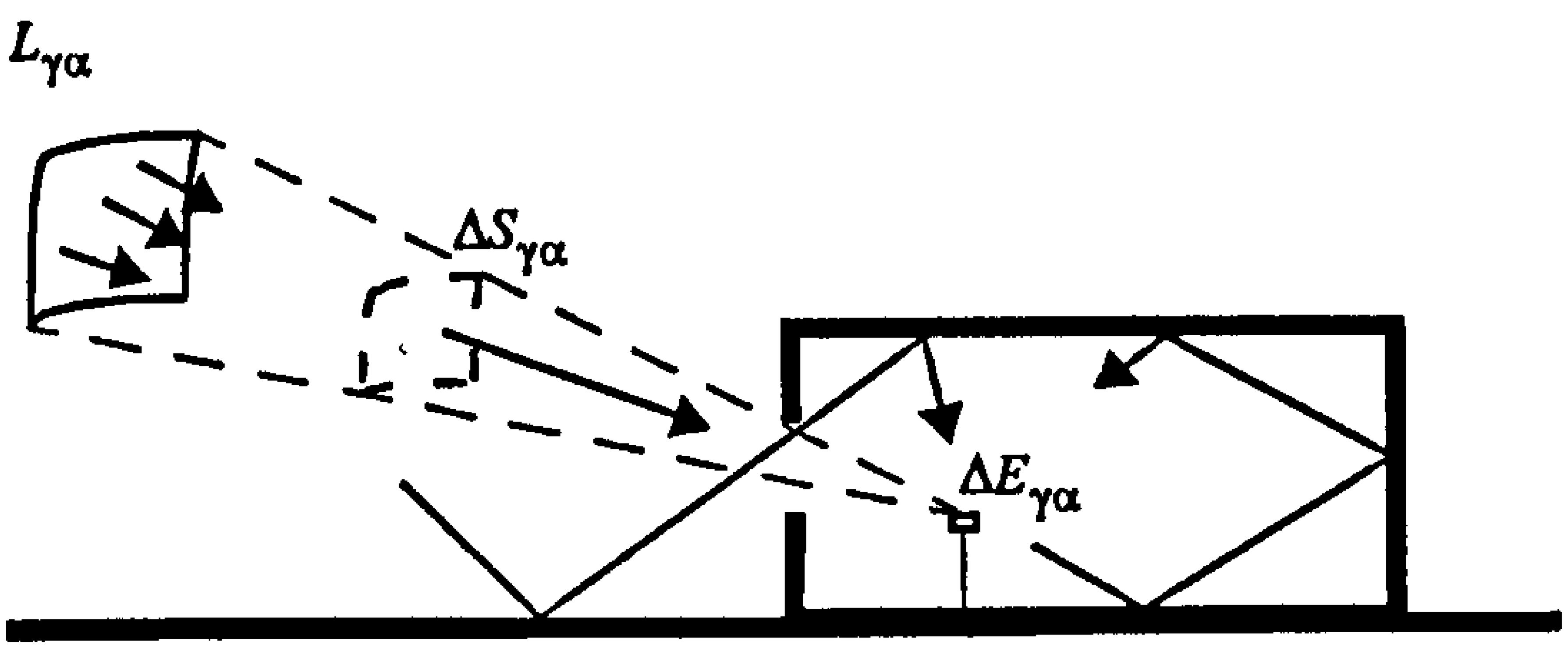


Figure 3-2 Daylight coefficient concept [re-drawn from Mardaljevic, 2000]

The total illuminance - $\Delta E_{\gamma\alpha}$ - [lux] produced at a point in a room due to each tiny zone at altitude γ and azimuth α is calculated by

$$\Delta E_{\gamma\alpha} = D_{\gamma\alpha} \cdot L_{\gamma\alpha} \cdot \Delta S_{\gamma\alpha} \tag{3-1}$$

where $L_{\gamma\alpha}$ and $S_{\gamma\alpha}$ are the luminance [cd/m^2] and angular size [m^2] of the sky element at altitude γ and azimuth α respectively. $D_{\gamma\alpha}$ is the Daylight Coefficient, a factor which depends on the geometry of the room and the surrounding buildings, the reflectance of many surfaces, and the transmittance of the windows. The Daylight Coefficient defines the sensitivity of internal illuminance to changes in the brightness of the sky element.

Following Eq 3-1 it is possible to define the daylight coefficient as

$$D_{\gamma\alpha} = \frac{\Delta E_{\gamma\alpha}}{L_{\gamma\alpha} \cdot \Delta S_{\gamma\alpha}} \tag{3-2}$$

From this, the total illuminance E [lux] produced at a point on the horizontal plane in a room can be obtained by integrating as follows

$$E = \int_0^{2\pi}\int_0^{\pi/2} D_{\gamma\alpha} \cdot L_{\gamma\alpha} \cdot \cos\gamma d\gamma d\alpha \tag{3-3}$$

This equation refers to the calculation of illuminance values at a point in a room. However as previously stated, light falling on this point comes from different surfaces in the room, the sky and external surfaces which produce inter reflections (that have to be taken into account). In order to account for all these inter reflections we can use finite elements calculation methods, i.e. considering the internal surfaces divided into finite areas and the external surfaces divided into finite angular zones [Tregenza et al., 1983]. The total illuminance E [lux] at a point is the product of D, S, and L for each finite element of the sky (sky patch) in the exterior and is determined using the following equation

$$E = \sum_{i=1}^{n} D_i \cdot S_i \cdot L_i \tag{3-4}$$

where n is the number of patches i at a substantial distance to be considered with the same angle from all points in the room. Therefore, the daylight coefficients can be calculated as vectors [Tregenza et al., 1983]. If the purpose is to calculate many points in the room then the array of values for D can be expressed as a matrix where E is a column vector with m elements. Therefore m x n will be the matrix of daylight coefficients D of n patches by m points and c will be a vector formed by the products of angular size and luminance Eq. 3-6.

A compact formulation of that matrix follows

$$E = D \cdot c \tag{3-5}$$

or in an expanded form

$$\begin{bmatrix} E_1 \\ E_2 \\ \cdots \\ \cdots \\ Em \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & \cdots & D_{1n} \\ D_{21} & D_{22} & \cdots & D_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ D_{m1} & D_{m2} & \cdots & D_{mn} \end{bmatrix} \times \begin{bmatrix} S_1 L_1 \\ S_2 L_2 \\ \cdots \cdots \\ \cdots \cdots \\ S_n L_n \end{bmatrix} \tag{3-6}$$

3.2.2 Mardaljevic's *Radiance* formulation of DC approach

The detailed formulation in Mardaljevic's work was partly dictated by *Radiance's* own algorithms. It uses three different Daylight Coefficient Matrices -DCM- computed through programs custom-written in IDL (Interactive Data Language) and Unix C-shell. Each proposed design needs a specific set of DCM and would need to be re-computed for every particular design of the building, the shading devices, or any substantial modification of physical properties or the surroundings.

The DC approach is computationally more efficient since it eliminates the need to repeat the inter-reflection calculation for every individual sky luminance distribution which is the most time consuming part of the simulation. Once the internal illuminance of every unit is computed, it is then possible to determine the internal illuminance for an arbitrary sky luminance distribution using relatively simple arithmetic operations on matrices [Mardaljevic, 2000a].

The implementation uses custom written data analysis programs to derive internal illuminance values from the DCMs. The total internal illuminance, E, for each calculation point (virtual photocell) due to sky and sun of arbitrary luminance is estimated as the sum of four illuminance components

$$E = E^d_{sky} + E^i_{sky} + E^d_{sun} + E^i_{sun} \tag{3-7}$$

where

E^d_{sky} is the direct component of illuminance due to sky

E^i_{sky} is the indirect component of illuminance due to sky

E^d_{sun} is the direct component of illuminance due to sun

E^i_{sun} is the indirect component of illuminance due to sun.

Each of the four illuminance components represents the influence of the surrounding geometry: the direct ones take into account the window and room configuration, obstructions outside the building, and the transmittance coefficient of glazing; the indirect components account for inter-reflected light, both inside and outside the room. These four components can be defined in terms of a daylight coefficient matrix (DCM) and a product of source angular size and source luminance. The following diagrams in Figure 3-3 describe they way they are predicted.

The original formulation by Mardaljevic was developed with the intention of testing the accuracy of the luminances derived through the DC approach against the BRE-IMDP validation data set. Therefore, the sky discretization schemes used had to correspond to the sampling pattern of the sky scanner[7] employed in the data measurements. Different shaped patches of different resolutions were used in the discretization schemes. One of these schemes was based on partitioning the sky into 145 'rectangular'[8] patches with each patch defined by lower and upper values for altitude and azimuth.This type of discretization gave a complete coverage of the sky hemisphere with no overlap. The other type of discretization used solid

7. PRC Krochmann sky scanner.

8. In fact they are not rectangular as they are a segment of the sky vault and therefore, part of the hemisphere, but named rectangular for brevity.

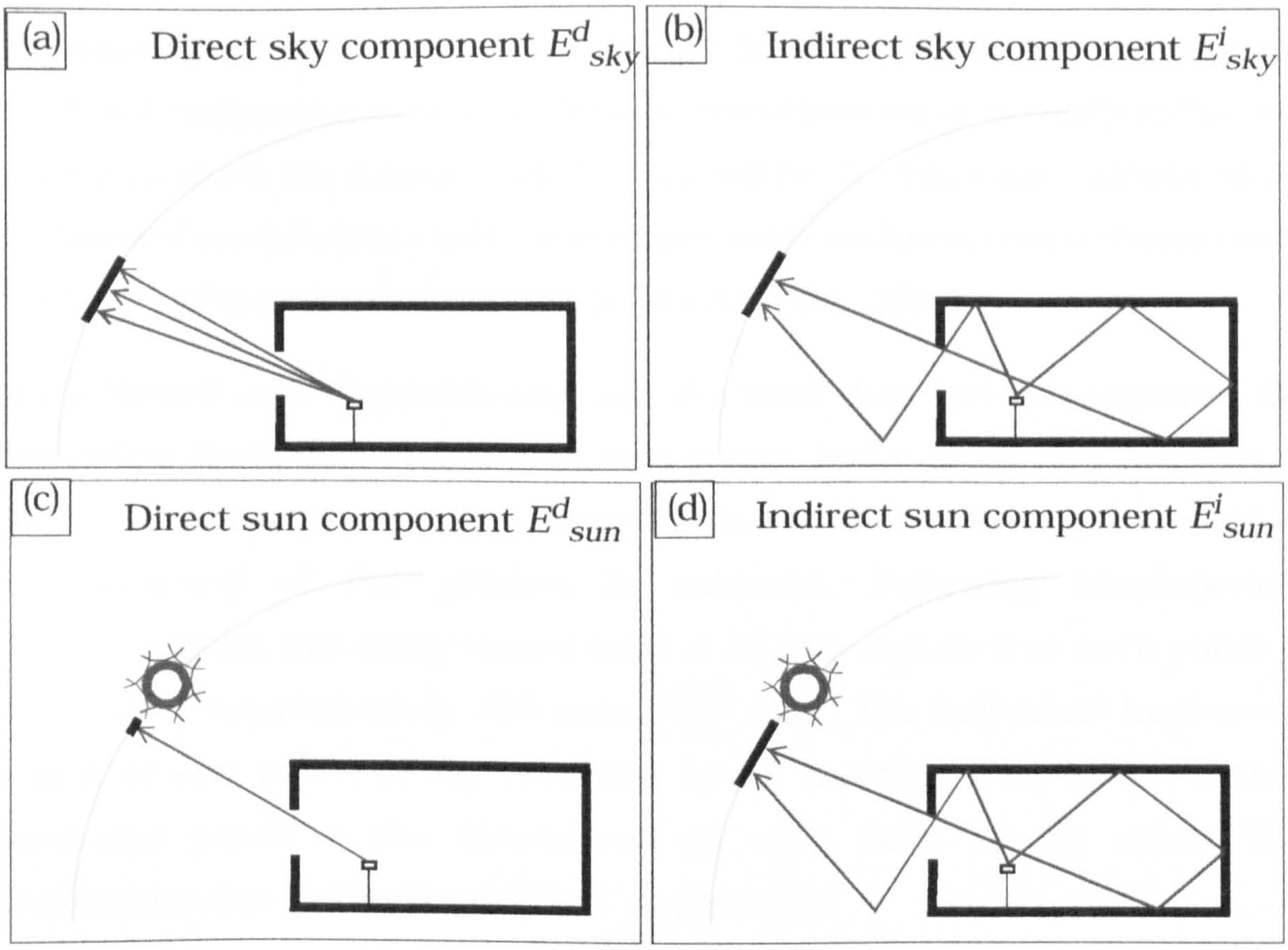


Figure 3-3 Components of illuminance (Mardaljevic, 2000)

angles, i.e. 145 'circular' patches. Similar to the pattern of the sky scanner, both patch schemes were numbered in a clockwise direction starting from North (N-E-S-W), on the edge of the hemisphere and moving towards the centre such that patch number 145 was the polar cap [Mardaljevic, 2000]

3.2.3 Direct Sky Component

For the calculation of the DCM for the direct sky component in Mardaljevic´s formulation, the sky hemisphere is first sub-divided into n= 145 'rectangular' patches in the pattern discussed above. Then, aimed rays from each calculation point in the room are distributed across a uniform luminance hemisphere. The use of a large number of rays to sample the patches for calculating the direct component reduces inaccuracies which might arise if a single ray is used to sample the patch centre only. This is because depending on the position of the calculation point, a single ray light source sampling (which is the usual mode for sampling the direct component for a solid angle/ circular light source in *Radiance*) might cause the direct component to be significantly overestimated or actually estimated to be zero since the source contribution will be, in this case, calculated on the basis of total source visibility or total source occlusion (even though only the centre of the source is sampled) [Mardaljevic, 2000].

In the 'aimed rays' approach only one sky vault description is required. No theoretical limit to the number of rays exists, and a sensitivity analysis is used to decide on the number beyond which no noticeable improvement in the sampling of the patches is achieved. Following Mardaljevic's implementation this study uses a total of 38,316 rays so that each patch is sampled by approximately 264 rays, $\left(\frac{38316}{145} = 264\right)$. The individual luminance values of any patch of sky returned by all the rays that intersect that particular patch is the illuminance at each point in the room. The illuminance due to the sky patch "*i*" is given by

$$\Delta E_i = \sum_{r \in T} L_r \cdot \cos\theta_r \cdot \Delta S_r \qquad \text{(3-8)}$$

where L_r is the ray luminance, θ_r is the ray zenith angle, and ΔS_r is the solid angle associated with he ray such that $\Delta S_r = \frac{2\pi}{N_r}$.

"*T*" is the set of rays *r* that, if not obstructed, intersect with rectangular patch "*i*" of extent $\Delta\alpha$ by $\Delta\gamma$ and centred on (α, γ), such that

$$T = \left\{ r{:}\left(\gamma - \frac{\Delta\gamma}{2}\right) \le \gamma_r < \left(\gamma + \frac{\Delta\gamma}{2}\right), \left(\alpha - \frac{\Delta\alpha}{2}\right) \le \alpha_r < \left(\alpha + \frac{\Delta\alpha}{2}\right) \right\} \qquad \text{(3-9)}$$

and for the particular case of the 'polar cap' patch

$$T = \left\{ r : \left(\frac{\pi}{2} - \Delta\gamma_z\right) \le \gamma_r \right\} \tag{3-10}$$

The direct DC is then computed using Eq 3-2 and Eq 3-8 as follows:

$$D_i = \frac{\sum_{r \in T} L_r \cdot \cos\theta_r \cdot \Delta S_r}{L_i \cdot \Delta S_i} = \frac{\sum_{r \in T} L_r \cdot \cos\theta_r}{L_i} \tag{3-11}$$

because

$$\sum_{r \in T} \Delta S_r = \Delta S_i \tag{3-12}$$

The direct sky illuminance is the result of multiplying the direct DCM by the vector product of the angular size and luminance of the rectangular sky patches.

3.2.4 Indirect Sky Component

The calculation of the indirect sky DCM is made using a division of the sky hemisphere into n= 145 circular patches defined using solid angles. A sole source of light of angle 11° is considered independently from each of these circular patches. The source is sampled with a single ray directed from the point to the source centre for the direct component which, after many samplings, the light transferred from a surface to the source is again a single ray to the source centre. The DC due to a circular patch, *i*, is then given by

$$D_i = \frac{\Delta E_{i(c)}}{L_{i(c)} \cdot \Delta S_{i(c)}} \tag{3-13}$$

The difference between the total DC and the direct DC is taken as the indirect component due to the sky.

Using these circular patches sampled just at their centres is less likely to be a problem for the indirect sky component than for the direct one since for the indirect component, many sampling rays from many different ray origins are used in the calculation. Although this circular sub-division of the sky does not offer complete sky coverage, the source angle has no effect because only the centre of the circular sky source is sampled. Since the indirect component arises from one or more reflections (i.e. it is less directional in nature than the direct component), hence the difference between a point and a patch is not likely to be so significant. It should also be added that it is not possible to specify a rectangular source angle in *Radiance* [Mardaljevic, 2000].

Although circular patches (subscript *c*) are used in calculating the DCM, the indirect sky illuminance result of multiplying that indirect DCM by the vector product of the angular size and luminance of the rectangular sky patches (subscript *r*). This is because the sum of the individual patches solid angles must be equal to the solid angle of the hemisphere i.e.

$$2\pi = \sum_{i=1}^{n} \Delta S_{i(r)} \tag{3-14}$$

3.2.5 Direct Sun Component

The direct sun component, like the direct sky component, is sensitive to potentially significant errors (either over or under estimations) due to single ray light source sampling. These errors may arise when there is a large difference between the actual sun position and the patch nearest the centre (sun displacement angle[9]). The direct component of sun illuminance is the

9. with a patch discretization based on the scanner pattern, the sun displacement angle with single ray light source sampling can be as large as 7°.[Mardaljevic, 2000]

most susceptible to error since the larger the sun displacement angle is, the larger the possibility that a point is estimated to be in the shade when it is actually in the sun or vice versa. [Mardaljevic, 2000]

However, in the same line with the reduction of errors performed in the direct sky component, the use of a large number of sources i.e. aimed rays, can reduce these errors [Mardaljevic, 2000]. Therefore, with *Radiance*, rays evenly distributed across a uniform luminance hemisphere are aimed from each calculation point in the room (a total of 5,056 rays). The luminance values returned by the rays are then used to construct the direct DCM for all the evenly distributed 5,056 points where the rays intersect the hemisphere. The illuminance due to a ray, *r*, is given by

$$\Delta E_r = L_r \cdot \cos\theta_r \cdot \Delta S_r \qquad \text{(3-15)}$$

and the direct DC can be given by

$$D_r = \frac{L_r \cdot \cos\theta_r \cdot \Delta S_r}{L_i \cdot \Delta S_r} \qquad \text{(3-16)}$$

i.e.,

$$D_r = \frac{L_r \cdot \cos\theta_r}{L_i} \qquad \text{(3-17)}$$

Amongst the 5,056 points on the hemisphere, the closest one to the actual sun position is located, and the column vector, δ, corresponding to this point in the '*m* x 5,056' matrix is multiplied by the sun solid angle and luminance in order to produce the direct illuminance due to the sun.

3.2.6 Indirect Sun Component

Similarly to the indirect sky component calculation, in order to produce the indirect illuminance due to sun, the circular patch whose centre is closest to the actual sun position is located, and the column vector β corresponding to this patch in the 'm x 145' matrix is multiplied by the sun solid angle and luminance due to the sun. The indirect sun component is less directional in nature than the direct component, usually resulting from one or more reflections, it is therefore, less sensitive to the sun displacement angle and errors that might result from single-ray light source sampling.

3.2.7 Total Illuminance

The total internal illuminance in Eq 3-7 (and Figure 3-3) can be expressed now in terms of daylight coefficient matrices as we can observe in Eq 3-18

$$\mathbf{E} = (\mathbf{D}^{d145} \times \mathbf{c}^{145}) + (\mathbf{D}^{i145} \times \mathbf{c}^{145}) + \mathbf{D}_{\delta}{}^{d5056} \cdot S^{sun} \cdot L^{sun} + \mathbf{D}_{\beta}{}^{i145} \cdot S^{sun} \cdot L^{sun} \qquad \textbf{(3-18)}$$

Where:

c^{145} is a column vector formed from the 145 products of angular size and luminance

D^{d145} is the direct sky DCM

D^{i145} is the indirect sky DCM

D_{δ}^{d5056} is the DC vector for the ray closest to the sun position

D_{β}^{i145} the DC vector for the patch closest to the sun position and the scalars

S^{sun} is the solid angle of the sun

L^{sun} is the luminance of the sun.

3.3 Thermal modelling

Building thermal simulation programs are increasingly used to predict energy consumption in non-domestic buildings. They address the calculation tasks at different levels and using diverse techniques. Most of these models use one of the following basic techniques: impulse response analysis, thermal network modelling or past performance i.e. empirical. Differences can be significant between the required inputs and the type of calculations they can perform. Some of them are used only to find the steady state heat gain or loss. Others reproduce the complex process which take place between the different surfaces of a building including the effects of thermal inertia of the building mass. The latter can simulate the dynamic response of the building. Within the non-domestic sector there is an understandable preference for dynamic thermal models over steady state ones. Dynamic models allow the prediction of seasonal energy consumption, effects of thermal mass and likelihood of passive solar gain or exclusion.

3.3.1 Simplified thermal response model

The model chosen in this thesis to perform thermal calculations is a simplified thermal network simulation model, see Section 3.1. This scheme uses structural element time constants, given by the stored-to-transmitted energy ratio, with a total of five parameters describing the thermal response of a single zone building. The parameters include the thermal mass of the building structure and of the air it contains, the heat loss by thermally rapid response paths (ventilation and glazing), the heat flow from the interior of the building to the thermal mass and from the thermal mass to the outside. Originally, the Exeter model was designed as a single zone model. However, with the inclusion of the thermal storage of internal walls and floors in the combined parameters, it can be applied also to cases with several rooms or partitions [Crabb et al., 1987]. The initial version developed by Crabb and Penman is used here with adaptations made by Hanby [1995].

3.3.2 Mathematical basis

Figure 3-4 represents the heat conduction or thermal storage process in the same way of an electrical circuit, using three heat conductionparameters, K_f, K_l, K_o, and two heat storage parameters, C_a and C_w.

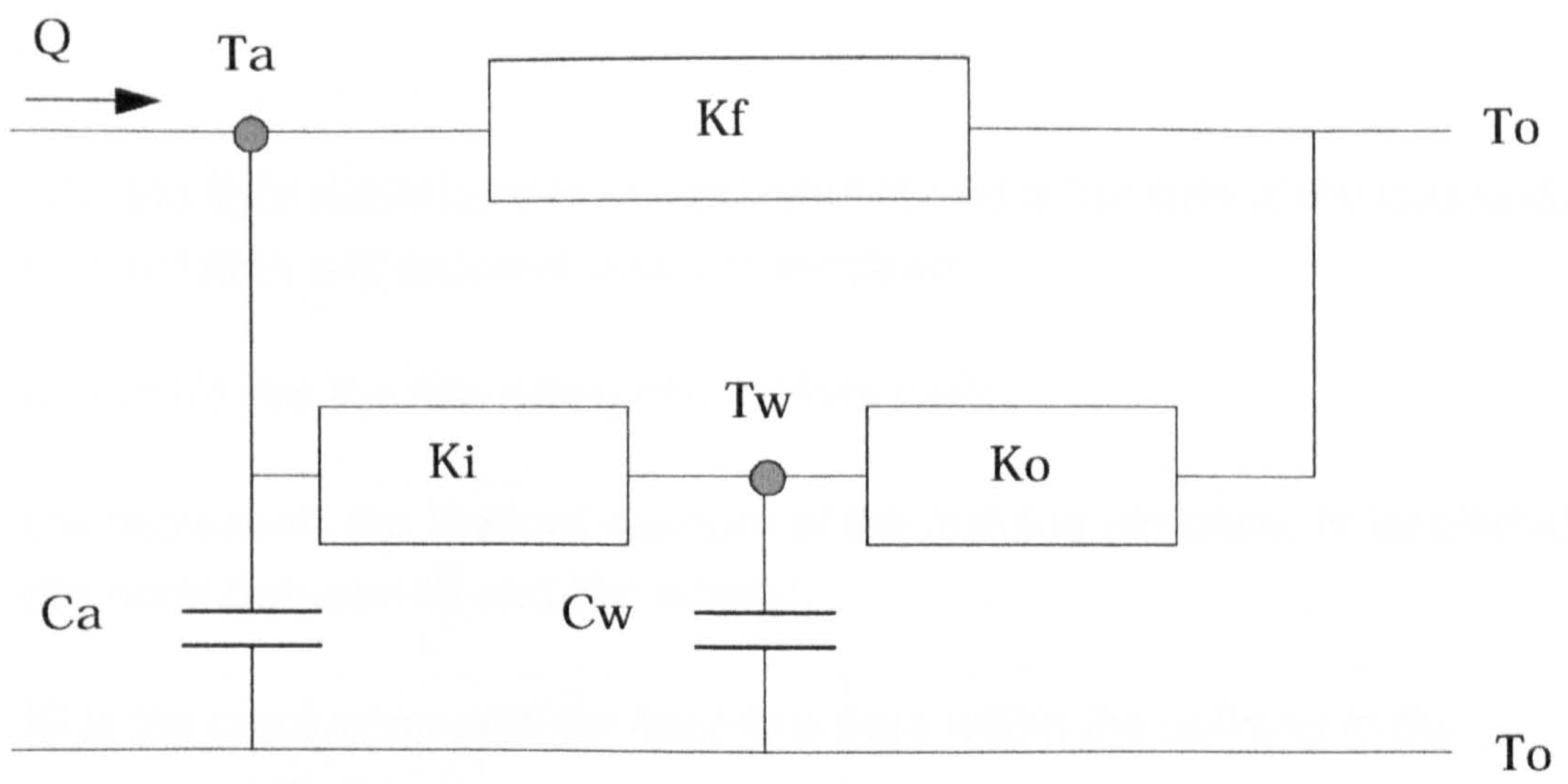


Figure 3-4 Single Nodal Model Diagram [re-drawn from Hanby et al., 1995] showing the process as an electrical circuit

Abbreviation	Variables	Units
System variables		
Ta	temperature of the air node	degC
Tw	temperature of the lumped structural node	degC
Boundary variables		
Q	total heat flux into/out of air node(HVAC plant, solar gain, casual gains)	kW
To	outside temperature	degC
Parameters		
Ca	thermal capacity of the air (fast) node	kJ/K
Cw	thermal capacity of the structure node	kJ/K
Kf	fast conductance	kW/K
Ki	air to structure conductance	kW/K
Ko	structure to outside conductance	kW/K

Table 3-1 Summary of variables for Simple Nodal Model

Where:

Kf is the lightweight heat loss conductance and is the sum of the losses due to ventilation and external doors or windows

Ki *and* Ko *are the heavyweight heat loss path.*

Cw *represents the thermal capacity of the building structure, is located at the node between* Ki *and* Ko*; where:*

Ki *is the conduction path for heat flow from within the building to the thermal cavity* Cw

Ko *is the path from this cavity to the outside.*

The relationships linking K_i and K_o describe the buildings' thermal mass characteristics; the sum of them is the sum of thermal resistance of the heavyweight loss path in the real building.

The ratio between *Ki* and *Ko* is associated with the relative distribution of thermal resistance to thermal mass in these paths. *Ca* models the thermal inertia of the air contained within the building. Lorenz and Massy suggest a factor to multiply *Ca* to account for convection depending on whether forced (*by* 4) or natural convection (*by* 5 or 6) is used.

The parameters needed as inputs in the model can be calculated from the geometry and the thermal properties of the building materials and the air.

The following differential equations represent the finite volume energy balance approach, conservation of energy in the air and structure node in this model:

$$C_a \cdot \frac{dT_a}{dt} = Q - Ki \cdot (T_a - T_w) - K_f \cdot (T_a - T_o) \tag{3-19}$$

$$C_w \cdot \frac{dT_w}{dt} = K_i \cdot (T_a - T_w) - K_o \cdot (T_w - T_o) \tag{3-20}$$

Amongst the strengths of this model is that the above equations (3-19 and 3-20) can be integrated analytically over a specified time period (usually one hour), thus avoiding errors due to discretization and numerical integration, and ensuring numerical stability. However, boundary conditions must be specified for a solution. Three sets of boundary conditions were used in the original EXCALIBUR program [Crabb et al., 1987]. These were:

- Building heating up constant rate of heat input until target temperature reached.
- Q is calculated such as to maintain a constant internal temperature.
- Building cools down, no heat input.

The current model has been modified to accommodate a greater range of functionality, which has precluded the use of an analytical solution. Accordingly, the above equations are discretised in time by the use of a fixed time step (a value for dt) and a numerical integration method (Euler). Numerical errors and instability are avoided by using a small time step, i.e. around 60 seconds.

The model is expressed as a fully-explicit, time marching, initial value problem. An initial value is arbitrarily assigned to the two state variables T_a and T_w. Equations 3-19 and 3-20 are rearranged to give the temperature changes:

$$dT_a = \frac{Q}{C_a} \cdot dt - \frac{K_i}{C_a}(T_a - T_w) \cdot dt - \frac{K_f}{C_a} \cdot (T_a - T_o)dt \tag{3-21}$$

$$dT_w = \frac{K_i}{C_w} \cdot dt(T_a - T_w) - \frac{K_o}{C_w} \cdot (T_w - T_o)dt \tag{3-22}$$

Then the temperatures at the next time step are given by

$$T_w' = T_w + dT_w \tag{3-23}$$

$$T_a' = T_a + dT_a \tag{3-24}$$

This simple numerical scheme has allowed cooling and heating to the zone, supervisory control of HVAC plant, to be added to the basic model.

3.3.3 Attributes of the Storage-Loss approach

The Storage-Loss approach for the calculation uses as a basic concept that the single capacitance model should store the same quantity of heat as the prototype under the steady-state conditions.

Advantages of this method are:

- Thermal properties and the location of the node can all be calculated in a simple manner from known thermal properties of construction.
- The distribution of insulation has some influence on the thermal response.

Disadvantages include:

- A symmetrical wall will always have its node placed centrally this is known to give an inadequate thermal response.
- When a hot climate is analysed, the node should be re-positioned to obtain more accurate results.
- The method does not give good results for variety of frequency-dependent functions.

3.3.4 Parameters estimation

A typical parameter input file for the Simple Nodal Model must include the following list of data:

Air node capacitance Ca (kJ K^{-1})
Structure node capacitance Cw (kJ K^{-1})
Capacitance of the internal walls Cp(kJ K^{-1})
Fast conductance K_f (kJ K^{-1})
Air to structure node conductance K_i (kJ K^{-1})
Structure node to outside conductance K_o(kJ K^{-1})
Air to internal wall node conductance K_p(kJ K^{-1})

Volume of air inside the room (m^3)
Maximum cooling capacity of HVAC plant (-kW)
Maximum heating capacity of HVAC plant (kW)
Cooling set point (^{0}C)
Heating set point (^{0}C)
Throttling range (^{0}C)

Estimation

Fast Conductance Kf This is the heat flow per unit temperature difference by ventilation/infiltration, plus fabric heat transmission that involves very low capacitance

$$K_f = \sum_i (A_i \cdot U_i) + (0.33NV) \qquad \textbf{(3-25)}$$

Where :

A= Area of the element [m^2]

U= Overall heat transfer coefficient [$W/m^2\ ^oC$]

V= Volume of the zone [m^3]

N= Number of air changes per hour [units h^{-1}]

'i' applies to all lightwight components

Heavyweight Conductances Ki, Ko The first step in assigning values to these conductances is to evaluate the overall thermal conductance through all the heavyweight elements of the zone. Where j applies to all heavyweight elements

$$K_t = \sum (A_j \cdot U_j) \qquad \textbf{(3-26)}$$

Separate values for Ki and Ko are then assigned once the location of the thermal capacitance has been decided.

Air capacitance Ca The thermal capacitance of the air in the zone is easily calculated from

$$C_a = \rho V c_p \tag{3-27}$$

where

V: is the volume of the zone

ρ : density

c: is the specific heat

However, experience has shown [Penman, 1990] that this model performs better if a much greater value of Ca is used. It is proposed that this reflects time delays due to air convection and thermal inertia in the lightways paths (glazing, roof, etc). It is suggested that the 'raw' value of Ca of Ca is multiplied by 4 (mechanically ventilated spaces) to 6 (naturally-ventilated spaces)

Structural capacitance Cw This is simply summing the thermal capacitances of the elements which contribute to the heavyweight thermal mass of the zone.

$$C_w = \sum_i (\rho_j V_j c_{p,j}) \tag{3-28}$$

Files are made according to the weight of the building mass and the HVAC plant functional characteristics defined. This enables the designer with flexibility to analyse different alternatives to perform more confident predictions. Outputs of the SNM are the hourly heating and cooling loads due to energy gains and losses and interaction between building elements.

3.4 Summary

The fundamentals of both 'engines' for calculating daylight coefficients and deriving irradiance and illuminances as well as the effects of thermal inertia of the building mass for this thesis have been presented.

The combination of these engines allows a more precise estimation of the energy fluxes when analysing the window-shading system. On one hand the daylight coefficient approach contribution brings the possibility of analysing more realistic sky luminance patterns and the effect of orientation on a building. Mardaljevic's *Radiance* implementation allows direct and indirect irradiation coming from the sun, the sky and any surrounding surface in the scenario to be analysed i.e. the adjacent urban environment and the shading device system. On the other hand, the linkage of the outputs of the lighting calculation (irradiation values) with the thermal model establishes a fast but accurate way for the estimation of heating and cooling loads. This, together with the energy consumption prediction due to electric lighting usage, constitutes a powerful tool for better informed design decisions and better quality control over performance assessments.

Later, a post-process of the hybrid model outputs allows the evaluation of energy consumption and carbon emissions[10] due to electric lighting, heating and cooling for different buildings design in various locales. Chapter 4 shows an application of the new technique to a base case and a comparison with a well established thermal calculation system.

10. CO_2 emissions depend on the primary energy generating process and the efficiency of the system for that locale. Therefore, every climate scenario is associated with a carbon emission pattern.

Chapter

4

The Hybrid Dynamic Lighting-Thermal Model II: Testing and Application

"A great building must begin with the immeasurable, must go through measurable means when it is being designed and in the end, must be measurable"

LOUIS KAHN

The foundations of the Hybrid Dynamic Lighting-Thermal Model (HyDiLM) were presented in Chapter 3, making explicit how this model was built and how it would fulfil the expectations of a precise modelling of shading devices in non-domestic buildings. Chapter 4 deals with a detailed description of the application of the model to a 'base case'. Additionally, an inter-model comparison against ESP-r, one of the validated calculation tools widely used in the building modelling sector is presented.

4.1 Description

As outlined in the previous chapter, the hybrid model HyDiLM is an implementation of two different calculation procedures (XDAPS and a Simple Nodal Model) for a more comprehensive task: the evaluation of shading devices' energy performance in non-domestic buildings.

The simulation framework was conceived to allow a rapid evaluation of building designs where a number of parametric alternatives need to be tested in parallel e.g. size of windows, shading device's design, building materials, glazing type, etc. The aim is to maximise the number of building scenarios that can be evaluated by exploiting efficiency features of prediction techniques.

The rationale for this methodology is grounded on the principle that accurate computation of irradiation and daylight values in the presence of shading devices should be determined using lighting simulation techniques. The dynamic thermal processes can be adequately accounted for by applying a simple nodal model relying for its accuracy upon the irradiation values provided to the thermal model. It is proposed that this combination may achieve a commensurate level of precision for the integral modelling process.

4.2 Process Scheme

This section presents the 'design' of the proposed Hybrid Dynamic Lighting-Thermal Model with a description of the elements in the form of a flowchart presented in Figure 4-1.

Building the geometry

The first step of the process starts by originating the base-case model geometry through *Radiance* commands. The UNIX version of *Radiance* allows to specify details of different building parameters more efficiently. Furthermore, C-shell scripts make possible to automate the production of

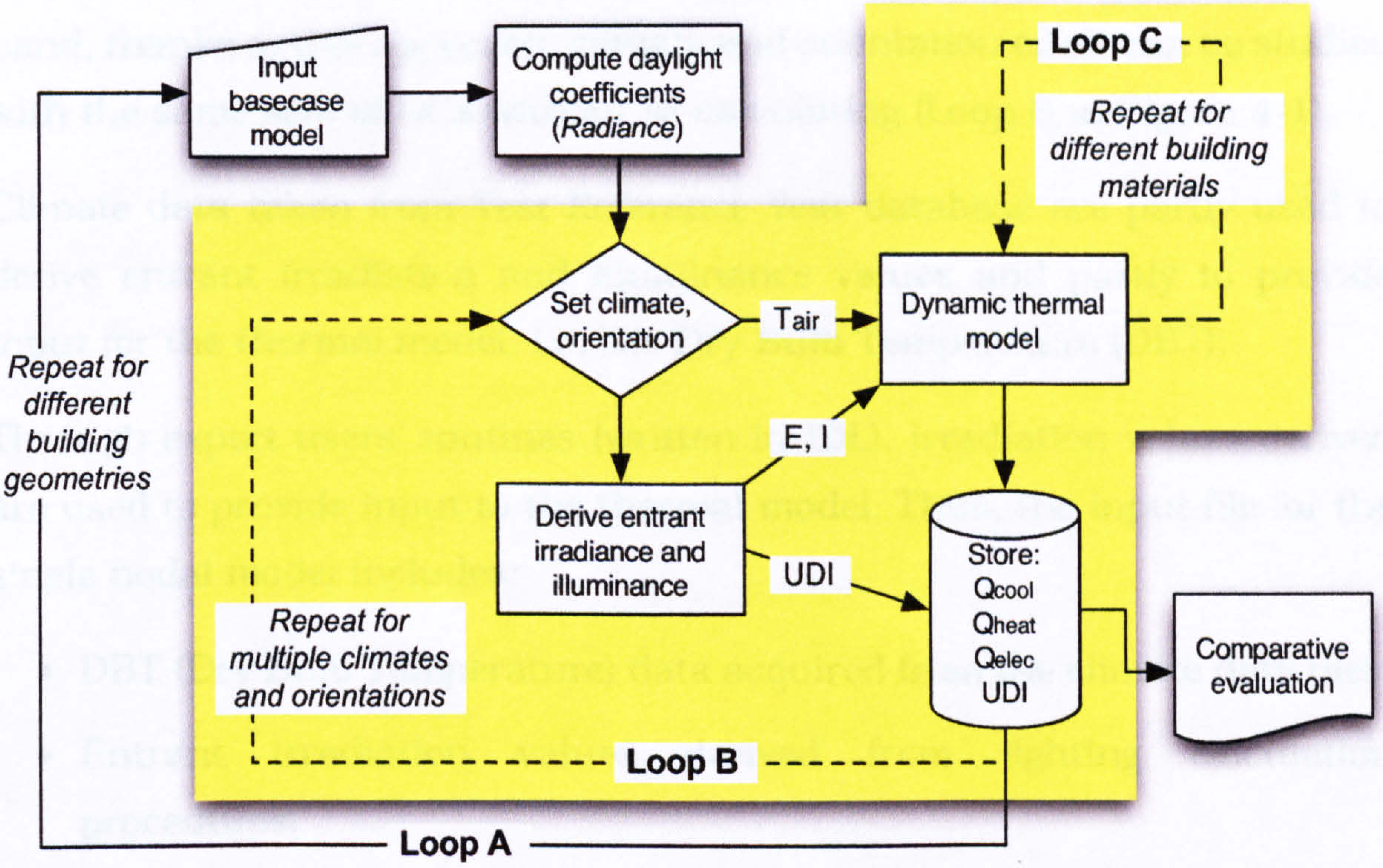


Figure 4-1 Hybrid Dynamic Lighting-Thermal Model Scheme

parametric cases, i.e. adding different shading device designs to the base case model.

Once the geometry of the model is completely built (as an input file), sets of Daylight Coefficients (DCs) can be calculated for points arranged as grids on a 'work plane' for illuminance values (horizontal) and for irradiation values on a plane on the inner side of the glazing pane (vertical), as shown in Figure 4-2.

Daylight Coefficients Calculation

A second step in the modelling process is the calculation of the Daylight Coefficients (DCs). One set of Daylight Coefficients per geometry is used to derive illuminance and irradiance values for different climate and orientation settings. However, it will be necessary to generate a set of DCs for every shading device design studied, i.e. different size, tilt, position, number, etc., even when it is applied to the same base case. This can be a limitation of this methodology, as the slowest operation within the process is to compute the ray-tracing function (Loop A in Figure 4-1). On the other hand, thanks to this approach, climate and orientation effect can be studied with the same sets of DCs without re-calculating (Loop B in Figure 4-1).

Climate data taken from Test Reference Year database are partly used to derive entrant irradiation and illuminance values and partly to provide input for the thermal model, i.e. the Dry Bulb Temperature (DBT).

Through expert users' routines (written in IDL), irradiation values derived are used to provide input to the thermal model. Thus, the input file for the single nodal model includes:

- DBT (Dry Bulb Temperature) data acquired from the climate data files.
- Entrant irradiation values derived from lighting calculation procedures.
- Irradiation values due to the heat dissipated by artificial lighting usage (which take in account the annual daylighting performance for the particular design case).

The illuminance values calculated in the first step are used:

- To analyse the daylighting performance of different shading devices' design. (The calculated illuminance values are stored in matrices which are used to assess the annual daylight performance of the room).
- To calculate the energy consumption due to electric lighting based on different users' occupancy scheme.
- To calculate heat due to electric lighting usage which will be summed with the rest of energy gains for an estimation of the total annual energy demand (within the single nodal model).

Metrics for the assessment of daylight performance were analysed and it was considered that UDI was the appropriate one for the study cases in this thesis (Section 2.3.3).

4.3 Inter-model comparison

As mentioned before, the Hybrid Dynamic Lighting-Thermal Model - HyDiLM- developed is an implementation of two different calculation procedures (XDAPS and Single Nodal Model). Both procedures have been validated through preceded research. The original XDAPS code implementation's custom written routines for calculating daylight coefficients and deriving daylight illuminances has been developed and validated against real sky conditions by Mardaljevic [Mardaljevic, 2000]. Modifications introduced later by Nabil allowing an automation of the process were also validated [Nabil, 2002]. The original thermal model known as EXCALIBUR completed a set of theoretical, analytical and empirical validation tests[11] [Crabb et al. 1987], therefore, it is considered that the Simple Nodal Model (SNM) which was based on it does not need further validation.

However, for the combined use of both programmes it is considered necessary to make a comparison between the use of HyDiLM as a whole and a traditional calculation software which has already been validated. The software chosen is ESP-r (Environmental Systems Performance - research) software [ESRU, 2000]. As outlined in more detail in Section 2.2, ESP-r is a dynamic thermal simulation program which was first introduced more than 25 years ago and has been in continuous development since then. It is primarily used in research to simulate the thermal performance of buildings under different climate conditions, heat gains, occupancies scheme, building construction and heating systems.

The comparison was made between HyDiLM and ESP-r using a room model consisting of an open plan office with one window (in a non-domestic building). Only one facade was facing the exterior and the rest were facing

11. *Theoretical:* The Lorenz and Massy scheme for obtaining the models parameters was checked. Subsequent mathematical derivation and algorithm coding was carried out by two of the authors and verified by the other. *Analytic:* The computed results for idealised conditions were compared with analytic calculations. *Empirical:* Model simulations were compared with measurements made at Tidcombe Lane Scool , Devon.

other offices either on the same floor or located above and below. This means that thermal interaction, for the purposes of this comparison, between these environments can be considered almost negligible. A model with similar properties of the room has been used for the HyDiLM, however some assumptions were made because of the differences between the two programs. The differences mentioned will be found in Section 4.3.3.

4.3.1 Geometry

For the comparison the base case has been used with an unshaded window. The room is 7 x 7 x 2.7 m. with a window of 7m width, 1.10 m. height, and 0.80 m sill height on one of the sides (Figure 4-2-***Left***).

For the determination of illuminance values a 1 meter grid of 36 virtual photocells was placed on the horizontal workplane. The distance between the walls and the first point of the grid was 1m. on each side. The distance between consecutive points was 1m. The determination of irradiation values coming through the window was made with a 0.22 by 0.35 meter grid positioned vertical on the inner side of the window at 0.05 m of the glazing plane. This represented 100 virtual photocells across the vertical plane.(Figure 4-2- ***Right***)

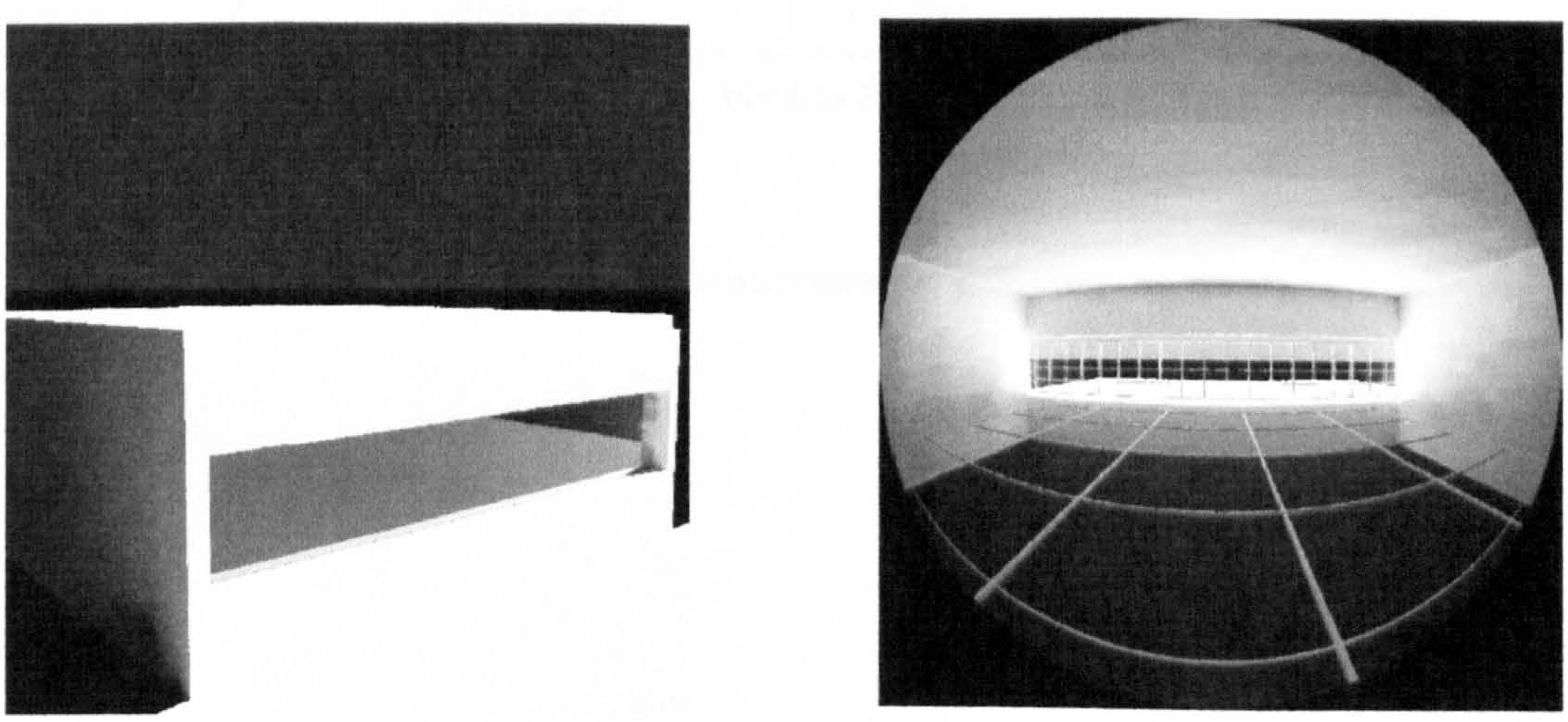


Figure 4-2 *Left*: External view of base case- *Right*: Fish-eye view with calculation grids

4.3.2 Building Elements

The room used for the comparison has three interior walls facing other internal rooms made of Breeze Bricks and plastered with Perlite Plasterboard. The external wall containing the window was modelled with two layers of bricks (Lt Brown Brick and Breeze Block) with an insulating material (Glass wool) and an air gap in between. For the ceiling and the suspended floor Wilton, Chipboard on top of a heavy mix concrete layer with steel structure was used. Further details regarding the building elements used are listed in Table 4-1with detailed data about them:

Element	Layer	Material	Thickness	Density	Conductivity
Internal wall	1	Breeze Block	0.150	1500	0.44
	2	Perlite Plasterboard	0.012	800	0.18
External wall	1	Lt Brown Brick	0.100	2000	0.96
	2	Glasswool	0.0750	250	0.04
	3	Air gap	0.050		
	4	Breeze Block	0.100	1500	0.44
Suspended Floor	1	Wilton	0.006	186.0	0.06
	2	Chipboard	0.0190	800	0.15
	3	Air Gap	0.050		
	4	Heavy Mix concrete	0.140	2100	1.40
	5	Steel	0.004	7800	50.00
Ceiling	1	Glasswool	0.100	250	0.040
	2	Ceiling	0.010	290	0.03
Glazing [a]	1	Clear Float	0.004	2500	1.05

a. Glazing Visible Transmittance 89%, Visible Reflectance 8%, Emissivity 0.83, Absortivity 0.05

Table 4-1 Materials' properties for building elements

Parameter	value	units
Air node capacitance	860	$kJ\ K^{-1}$
Structure node capacitance	2724.408	$kJ\ K^{-1}$
Capacitance of the internal walls	39365.0	$kJ\ K^{-1}$
Fast conductance	0.088401	$kW\ K^{-1}$
Air to structure node conductance	0.028278	$kw\ K^{-1}$
Structure node to outside conductance	0.005655	$kw\ K^{-1}$
Air to internal wall node conductance	0.426	$kw\ K^{-1}$
Volume of air inside the room	132	m^3
Maximum cooling capacity of HVAC plant	15	kW
Maximum heating capacity of HVAC plant	15	kW
Cooling set point	22	^oC
Heating set point	19	^oC
Throttling range	1	^oC

Table 4-2 Parameters values calculated for a base-case analysis

For the particular case used for the inter-model comparison with materials specified in Table 4-1, the calculated parameters are shown in Table 4-2

4.3.3 Climate, Orientation and Gains

The test room was modelled for a location with the window facing South (Birmingham, UK).

Hourly solar irradiation data from Birmingham IWEC WMO 035340 (sourced from IWEC/DoE) were loaded, and for every daylight hour in the year, i.e. where the irradiation was greater than zero (for this data-base: 4408 hours), the following was done:

- The sun position was calculated using the geographical position and time registered on the TRY. Irradiance was converted to illuminance, and the luminance of the sun was calculated. A luminous efficacy of 120 lumens/watt was used[12].

12. A simple constant value for the luminous efficacy was used, but more complex models could be used if desired.

- The sky clearness index was calculated using the illuminance and the sun altitude.
- A sky model was generated as a blend of the CIE standard overcast sky and the Matsura intermediate sky model using the illuminance and the sun position. Proportions of each sky model established by a mixing factor were used in the blend.[13]
- The luminance of each of the 145 sky patches were calculated from the sky model.
- The direct and indirect illuminances due to the sky were then derived using the corresponding DCMs and the angular size and luminance of each of the sky patches.
- The direct and indirect illuminances due to the sun were also derived using the corresponding DCM vectors (i.e. patches) closest to the sun positions and the solid angle and luminance of the sun.
- The total internal illuminance, due to the sky and sun, was then determined by the summation of those four illuminance components. This was carried out for each of the 36 points across the workplane.
- The irradiance of each of the 145 sky patches were calculated from the sky model.
- The direct and indirect irradiance due to the sky were then derived using the corresponding DCMs and the angular size and luminance of each of the sky patches.
- The direct and indirect irradiance due to the sun were also derived using the corresponding DCM vectors (i.e. patches) closest to the sun positions and the solid angle and luminance of the sun.

13. The mixing function for this sky blend was tuned to the 754 skies in the validation data set (used for validating the XDAPS formulation). Furthermore, on the basis of the Perez clearness index, the validation data set skies were found to be reasonably representative of the range of the skies in the TRY database. Thus, this sky blend can be considered to offer a credible approximation to the range of skies from which the TRY was derived [Mardaljevic, 2000]

- The total internal irradiation, due to the sky and sun, was then determined by the summation of those four irradiance components. This was carried out for each of the 100 points across the vertical plane in the inner side of the window.

This calculation meant that 4408 x 36 x 4 (i.e. 634,752) internal illuminances values derived in the process since four components of illuminance were derived for each daylight hour for each point. In consequence, there were 4408 x 100 x 4 (i.e. 1,763,200) irradiation values derived in the process since four components of irradiance were derived when the irradiation was greater than zero for each point. The values corresponding to the rest of the hours were filled with 'zeros' when producing the input file for the thermal model.

Other settings were as follows:

External Gains - The external gains considered were those due to irradiation coming through the external facing wall which contains the window (opaque element), and infiltration through the window.

Internal gains - To include: people, equipment and lighting[14].

Occupancy pattern - As stated previously the pattern chosen for the analysis of thermal loads was that of an office space. The occupancy was defined based on 10 working hours per day (from 9:00 to 19:00) with no exception made for weekends. Based on this pattern all the schedules were planned heating and cooling plants, people and equipment, lights and air infiltration from outside.

People: An occupancy density of 1 person per 7m2 was used based on CIBSE recommendations of 1 person per 6-10m2 for city centre offices

14. Q value is obtained by summing the external and internal gains. A simplication of this model is that Qsolar is considered directly affecting the internal air temperature not counting the effect of internal surfaces that can receive irradiation and dissipate it through convection.

[CIBSE, 2006]. A sensible load[15] of 100W and a latent load of 30W per person were assumed, that is to say 700W of sensible loads and 210W of latent loads for the whole room.

Lighting: For this comparison the heat due to artificial lighting was calculated with different approaches for the two programs:

- For the HyDiLM an on-off switching scheme was applied. Therefore, whenever during working hours the illuminance level at any of its virtual photocells fall below 500 lux, artificial lighting at working plane height is set on to produce 500 lux. Then the heat produced by the lighting system is added to the rest of gains for the thermal calculation.
- For ESP-r the guidelines for offices were followed, i.e. an average installed power density for lighting at 12W/m^2 using fluorescent-triphosphor lamps. The surface of the room is 49m^2 which results in 588W of sensible loads. A proportion of this value is radiant energy and the rest is conducted/convected. Based on recommendations for the type of lamp used, the radiant and convected components were considered to be 30% and 70% respectively.

Personal computers and office equipment: They result in heat gains to the room equal to the total power input. Recent recommendations have concluded that a cooling load of 15 W/m2 is adequate to cope with small power consumption for all but the most intensive needs. Therefore for heating gains from office equipment were 15 W/m^2 x 49m^2 = 735W.

4.3.4 Results

A comparison of the output values for heating and cooling loads from both programs is given in Table 4-3. They show a strong similarity for heating and cooling loads. HyDiLM gives back a heating load of 2319 kWh per year and a cooling load of 1341 kWh compared to 2224 kWh and 1336 kWh of

15. Sensible loads are considered in both calculations, however latent loads can only been considered in ESP-r as one of the simplification of the Single Nodal Model is the estimation of sensible loads.

ESP-r respectively. That means a 4.3% of difference in the heating loads and 0.3% in cooling loads.

	Heating kWh/ year	Cooling kWh/ year	Total Annual Irradiation kWh
ESP-r	2224	1336	4550
HyDiLM	2319	1341	4745
Dif%	4.3	0.3	4.28

Table 4-3 Results comparison between ESP-r and HyDiLM

Some other parameters involved in the calculation process are explored such as the irradiation coming through the window and the result air temperature inside the room. Regarding irradiation values, the total annual irradiation values for both models are in Table 4-3, ESP-r gives 4550 kWh for the whole year whereas the HyDiLM presents 4745 kWh, this means an over prediction of 4.28% for HyDiLM over ESP-r.

Figure 4-3. shows the correlation of hourly irradiation values for both programs, again with a good agreement between them.

The HyDiLM counts for hourly values of direct and indirect irradiance due to the sun and sky across the glazing pane. ESP-r counts solar radiation coming from outside.

The over-plotted purple line describes the agreement between both set of values, the black one describes the best possible agreement between them.

A plot of hourly air temperature values calculated for both plants is presented in Figure 4-4. The upper part of the plot shows hourly values of ambient Dry Bulb Temperature for the whole year. Differences can be appreciated between plots where HyDiLM appears allowing minimum

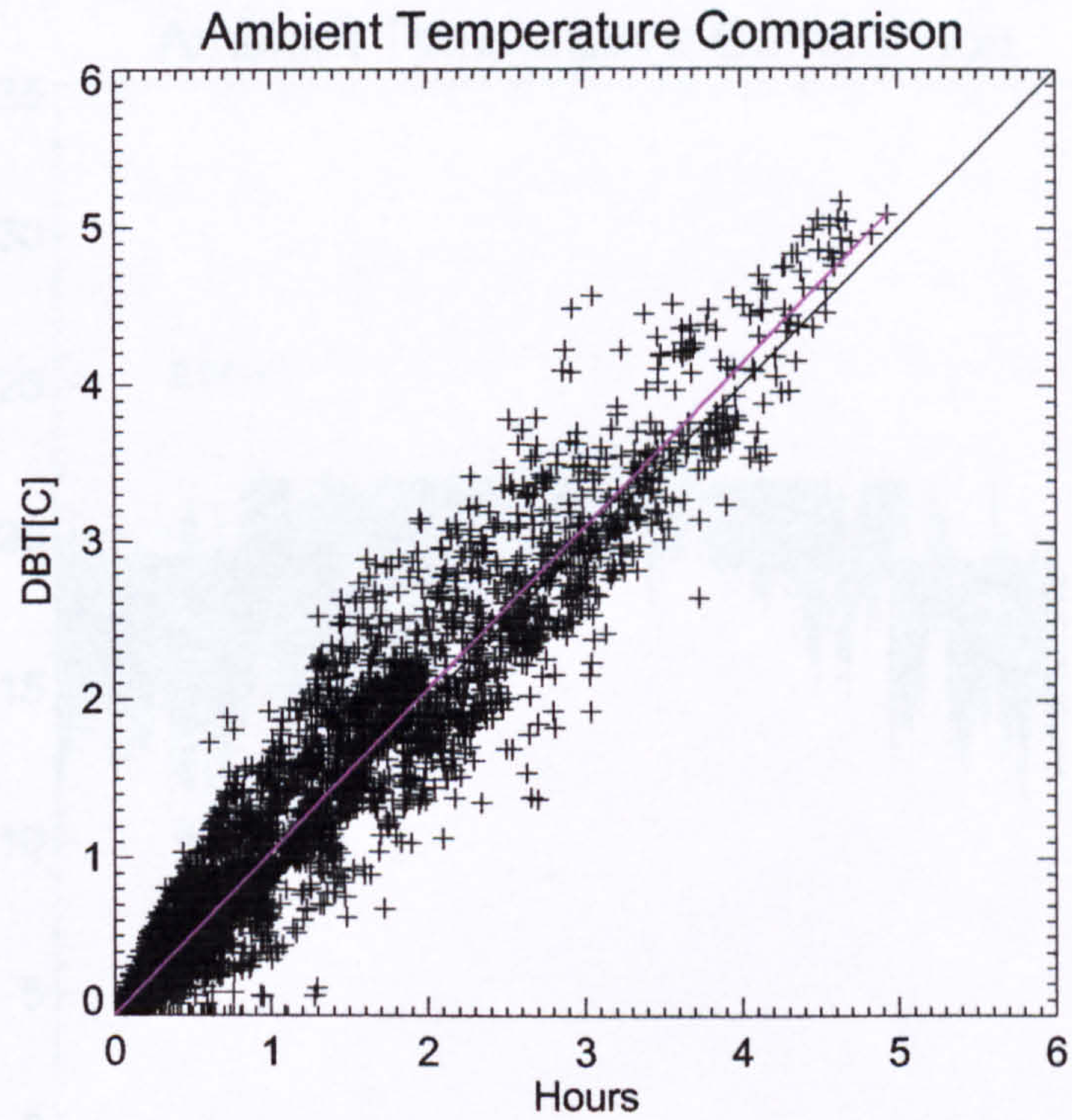


Figure 4-3 Irradiation correlation between ESP-r and HyDiLM

temperatures than ESP-r before setting the plant 'on'. On the other hand ESP-r shows more maintained values around the setting points (19 and 22 C). It is noticeable that throttling range values work different, for HyDiLM it has been fixed at 1K and works between the value half degree below and above the set point. This means that the plant is allowed to reach half degree higher for the heating function and half degree less for the cooling function. For ESP-r the temperature of the set point is reached and maintained in both functions. This difference can be the reason for higher values in energy demands performed by HyDiLM compared to ESP-r.

The lower part of Figure 4-4 shows an amplification for some hours of January only, the aim of this plot is to show the differences that models have while performing their calculation on an hourly base. Although some differences can be appreciated where ESP-r drops the ambient temperature to lower values than HyDiLM, they follow a common pattern of variations in the final ambient temperature.

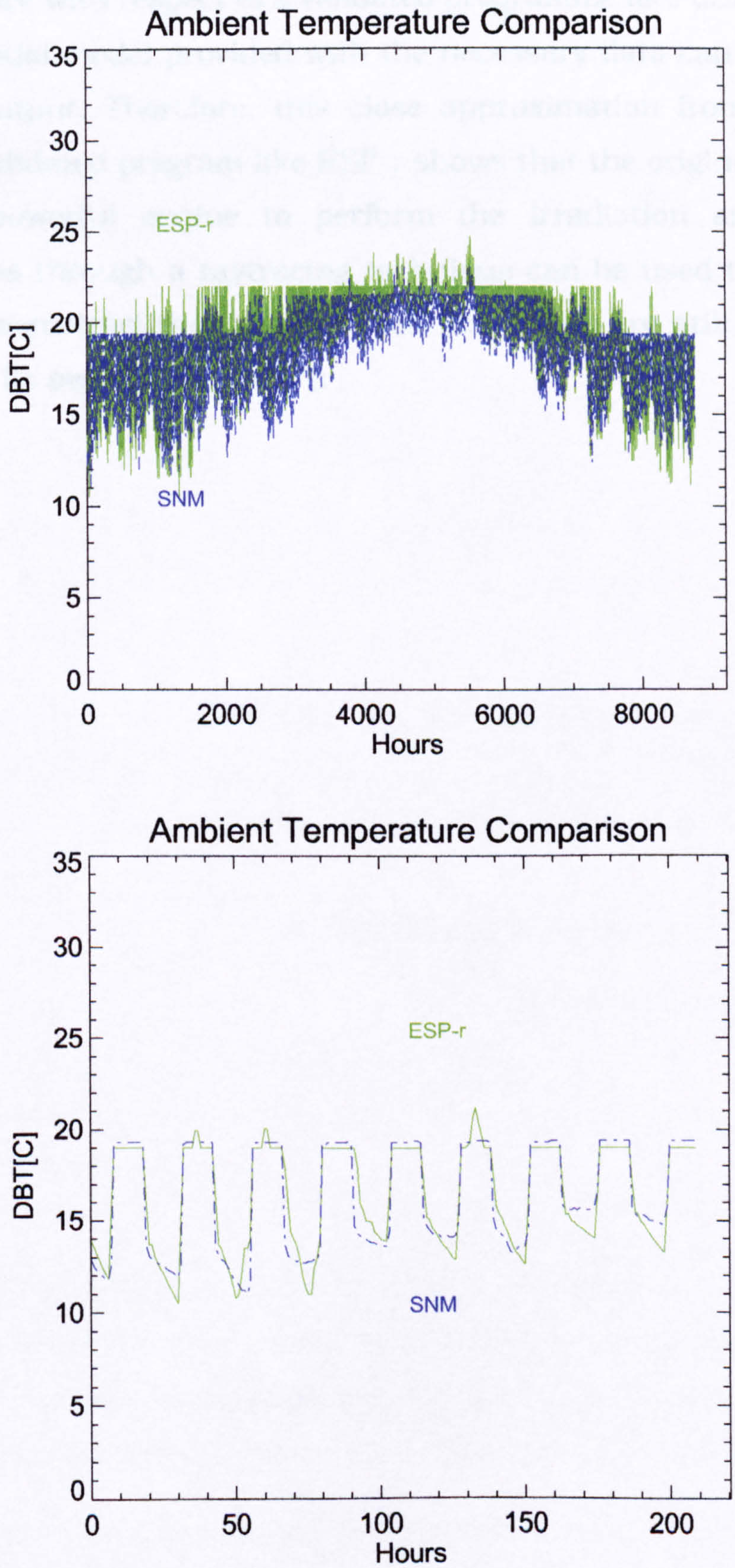


Figure 4-4 Room Dry Bulb Temperature comparison for Birmingham climate(Superior: Annual- Inferior: January)

Under similar conditions HyDiLM is performing within an acceptable range of confidence with respect to a validated programme like ESP-r proving that a single nodal model provided with the necessary data can ensure reliable thermal output. Therefore, this close approximation from HyDiLM to a strongly validated program like ESP-r shows that the original hypothesis of using a powerful engine to perform the irradiation and illuminance calculations through a raytracing technique can be used to analyse more complex geometries that programmes like ESP-r are still not prepare to handle on its own [ESP-r, 2007].

Chapter

5

Performance analysis of shading devices with HyDiLM

"From the categorical eloquence of the single opening of the Pantheon to the magical complexity of the Germanic Baroque via the increasingly finely wrought Gothic cathedrals, natural light has been a deciding factor in the quality of space"

RAFAEL SERRA (FROM RENEWABLE AND ENERGY REVIEWS, 2, 1998, PERGAMON)

The modelling tool named 'HyDiLM' (Hybrid Dynamic Lighting Thermal Model), presented in this thesis, is intended to assist building design in decreasing energy consumption due to lighting, heating and cooling while using shading devices integrated with the entire architectural project.

A classification and description of different types of shading systems was given in chapter 2, they included exterior elements, the glazing system itself (as it includes low shading coefficient glasses), intermediate elements and interior control devices.

The consideration of the quality of the illuminated environment (i.e. the distribution of suitable levels of illuminance related with a given task throughout the work plane and throughout the different seasons of the year) concurrently with thermal comfort conditions and savings in energy consumption deals with the challenge of an integrated approach. Furthermore, their influence in greenhouse gas emissions was considered, with the aim to develop weighted design decisions affecting integral energy considerations and its consequences.

Firstly, a complete description of the characteristics of the geometry selected for the experiment is provided including the materials' properties and the different alternatives of shading devices studied.

Secondly, the variables studied such as climate and orientation are described together with the criteria that influenced the selection.

Chapter 3 described the fundamentals of both original models which were the base for this hybridization whereas chapter 4 showed an application of the hybrid model to the so called 'base-case' and a comparison with a validated thermal model. Here, in chapter 5, an account of the calculations applied to the designed experiment is outlined showing a step by step development together with a synthesis to clearly indicate where in the process each step takes place.

In this chapter, the quantitative and qualitative parameters used to evaluate external shading device alternatives for different locale and orientations are presented, then results for two particular climate cases are analysed showing how shading device design affects energy consumption

5.1 Modelling Non-domestic buildings with shading devices

These experiments aim to apply HyDiLM to a range of particular cases which were taken from the common practice of external shading devices used for non domestic buildings. Some of these have been used in previous studies to evaluate the influence of the variables of a window-shading system i.e., external shadings, advanced glazing materials, window to wall ratio analysis, etc.[Kapur, 2004], [Tzempelikos, 2007], [Loe, 2003].

Selection of cases was based upon meeting the minimum requirements of non-domestic buildings in developing countries where the use of double glazing or highly industrialized building materials is not common. Non-domestic buildings include a wide range of buildings, however purpose built buildings for education (mainly classrooms) and offices are a big percentage within this generalisation. Therefore, the focus of non-domestic buildings on education and offices in developing countries determined the selection of most of the components for the present experiment. The proportions and dimension of the base-case, as well as the materials and type of shadings were chosen to meet the above mentioned requirements. The consequent intrinsic contextual characteristics that should be addressed are low cost and maintenance rates. These leave most of cutting-edge technologies such as multi-pane glazing, advanced glass technology, etc., beyond consideration for this study.

5.1.1 Geometry

The selected geometry represents a generic room of a non-domestic building. It is acknowledged that generalisation cannot represent the vast scope of all kinds for non-domestic buildings and rooms. The room layout here is based on standards for typical sized classrooms catering for 20-30 pupils in different latitudes i.e., United Kingdom [SBDU, 2002], Spain [Perez Castillo, 2004], Argentina [MCEN, 1996], etc. However, it could be also an office room or a module within an office building with an open plan layout.

Room characteristics are similar to those of the one used in Section 4.3.1, and it is assumed to be built with standard building materials and surfaces with standard characteristics.

The "working plane" for illuminance evaluation was considered to be horizontal at 0.85 m. height from the floor.

Reflectivity. White matt material is used for walls and ceiling (with a reflectivity of 0.6), brown matt for the floor (0.2) and grey matt for the surrounding external surfaces (with a reflectivity of 0.2).

Transmittance. The glazing material is a clear 6mm. single glazing pane which has a 87% of transmittance [Pilkington, 2007][16].

Building materials For this experiment one set of building materials has been tested. However, within the capabilities of the model is the possibility of introducing changes to the input file of the Simple Nodal Model. Therefore, other sets of building materials can be tested, in HyDiLM scheme this can be processed within Loop C - Figure 4-1 -.

Points Grid. For the calculation of illuminance values a 1 metre grid of (36) virtual photocells was placed on the horizontal workplane. For the calculation of irradiation coming through the shading window system, a 0.22 m by 0.35 m grid was placed on the inner side of the window plane (100 virtual photocells). These grids are similar to the 'base case' studied in Section 4.3.1.

5.1.2 Shading Devices

In order to carry out parametric studies of various shading devices designs, C-shell scripts have been written to produce vertical and horizontal louvres and overhangs 'attached' to the base-case.

16. As mentioned before this choice of glazing material is related with the fact that in developing countries most of the glazing, particularly in educational and public buildings, is the most extensively used. This author took part in a large survey of educational schools for the World Bank in Northwest Argentina, which verified that 100% of the buildings included in that survey -more than 500- used single glazing.

UNIX version of *Radiance* plus C-shell scripts allowed the automation of the process to produce different shading devices applying them to the base case geometry and to perform the ray tracing calculations all within a single script. This constitutes a note of quality assurance throughout the process as it can be controlled to perform repetitive operations lowering error probabilities by reducing human intervention per cycle. Cases analysed include vertical and horizontal louvres at different tilts and external light-shelf at different heights from the floor level (Figure 5-1). The identification of the degree of shading that these devices can devise is made on the lower right corner of every plot as follows:

U - Unshaded

LS - Low Shaded

MS - Medium Shaded

HS - Highly Shaded

Vertical Louvres

Three different alternatives for angles were tested (Figure 5-1): tilted 45 degrees to the right - identified as Vm45-; perpendicular to the glazing plane - identified as V0 -; and 45 degrees to the left - identified as Vp45 -.

Size: The width of each vertical louvre was 0.20 m with a gap of 0.20 m between them.

Reflectance: 30% reflectance gray material was assumed for louvres considering they can be made of low maintenance materials (i.e, precast concrete) and being exposed outdoors.

Horizontal Louvres

Two different alternatives of angles were tested: parallel to the sill plane (0 degrees) - identified as H0 -; and tilted 45 degrees -identified as H45 -.

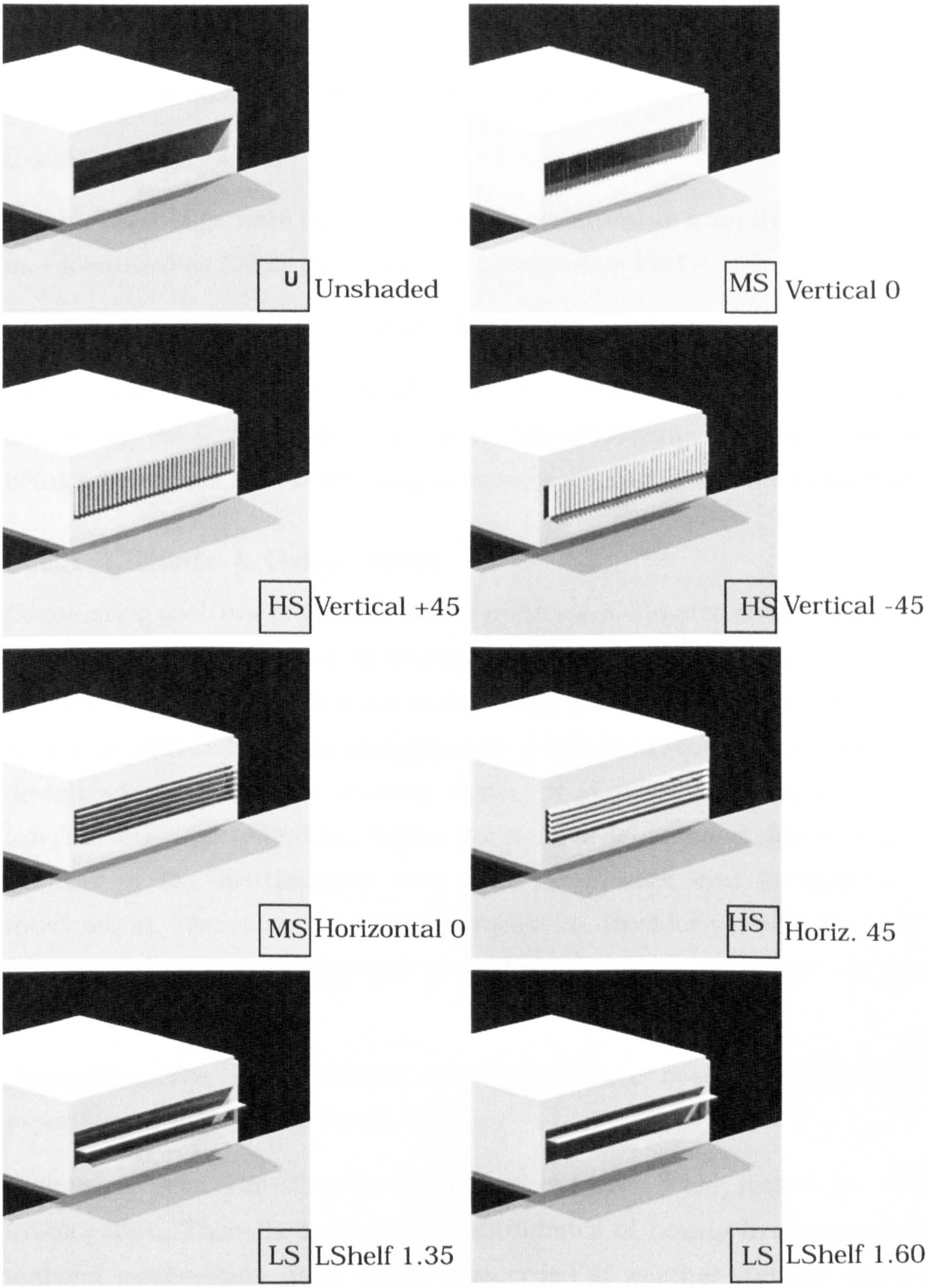


Figure 5-1 Shading Devices alternatives

Size: The width of each horizontal louvre was 0.20 m with a gap of 0.20 m between them.

Reflectance: A 30% reflectance gray material similar to horizontal louvres.

Exterior 'Light-Shelves'

Height: overhangs were placed at two different heights from the floor: 1.35 m. - identified as 1000 -, and 1.60 m - identified as 1001 -.

Size: The width of the overhang was 0.60 m.

Reflectance: A 60% reflectance white material was assumed for overhangs, addressing the fact that the function of these overhangs is close to that of being a light shelf, i.e., redirecting light from exterior inside the classroom.

5.1.3 Climate & Orientation

Considering each one of the geometries in different climates and for different orientations the same set of Daylight Coefficients (DCs) was reused to perform calculations. This is one of the significant features of this approach: once a set of DCs has been calculated for a proposed scenario i.e., building design with a particular shading device, it is possible to compute the internal illuminance and irradiation (for this particular case), under a large number of sky distributions with little extra work and minimal user intervention. Therefore, the looping process to consider variables such as climate and orientation can be included altogether in one script and run efficiently.

Orientation. The four cardinal orientations have been tested for this experiment (North, East, South, West).

Climate A selection of twelve different climates were tested for this investigation. There is currently an abundance of hourly irradiation and ambient temperature data, which is recorded at weather stations around the world and which can be readily downloaded from the Internet [EERE, 2007].

The climate data used in this study were chosen to present a wide range of scenarios based on the variation of multiple parameters: latitude, altitude, closeness to the sea, etc. It was intended to represent many of the possibilities which may be faced when calculating the energy performance for non domestic buildings. Latitude can be one of the main influences when evaluating daylighting performance while for thermal evaluation, variations in temperature and humidity can significantly affect the performance of two locales at similar latitudes. The location and climates chosen are listed in Table 5-1.

As described in Chapter 3, Mardaljevic's implementation of DCs (XDAPS) used a mixing function for the sky blend model which had been tuned and proven valid for typical UK skies. Tuning the sky mixing function requires values for the illuminance incident on the main four cardinal vertical orientations. In Mardaljevic's case data measurements were part of the data set from the BRE-IMDP sky monitoring study, whereas in the other locales studied these data were not available. Therefore, the mixing function could be fine tuned for skies typical of other climates. Instead, the same mixing function tuned for UK skies was thus used here for deriving daylight illuminances and irradiance inside the office model with other climate files as input. Such approximation was considered as acceptable for the evaluation of daylight and energy performance of the window-shading system in climates of different characteristics.

In this thesis, a criteria was expressed at the beginning of the current section with respect of developing countries conditions for the energy consumption evaluation. However, in order to simulate the same kind of room in a variety of latitudes and climates, that criteria remained flexible for the selection of climate database.

Location (City and Country)	Latitude	Longitude	Climate
Adelaide, Australia	34.93S	138.52E	Mediterranean (Dry Summer)
Arequipa, Peru	16.32S	71.55W	Arid Desert
Algiers, Algeria	36.72N	3.25E	Highlands
Belem, Brazil	1.38S	48.48W	Tropical Monsoon
Buenos Aires, Argentina	34.49S	58.53W	Humid Subtropical
Fairbanks, Alaska	64.49N	147.52W	Sub polar
Guangzhou, China	23.13N	113.32E	Mediterranean Dry winter
Havana, Cuba	22.98N	82.40W	Tropical Wet & Dry
London, U. Kingdom	51.15N	0.18W	Marine
Murcia, Spain	37.79N	0.80W	Semi Desert
Punta Arenas, Chile	53.00S	70.85W	Polar Tundra
Sapporo, Japan	43.05N	141.33E	Humid continental

Table 5-1 Coordinates of location studied and climate classification [Ahrens, C., 1994]

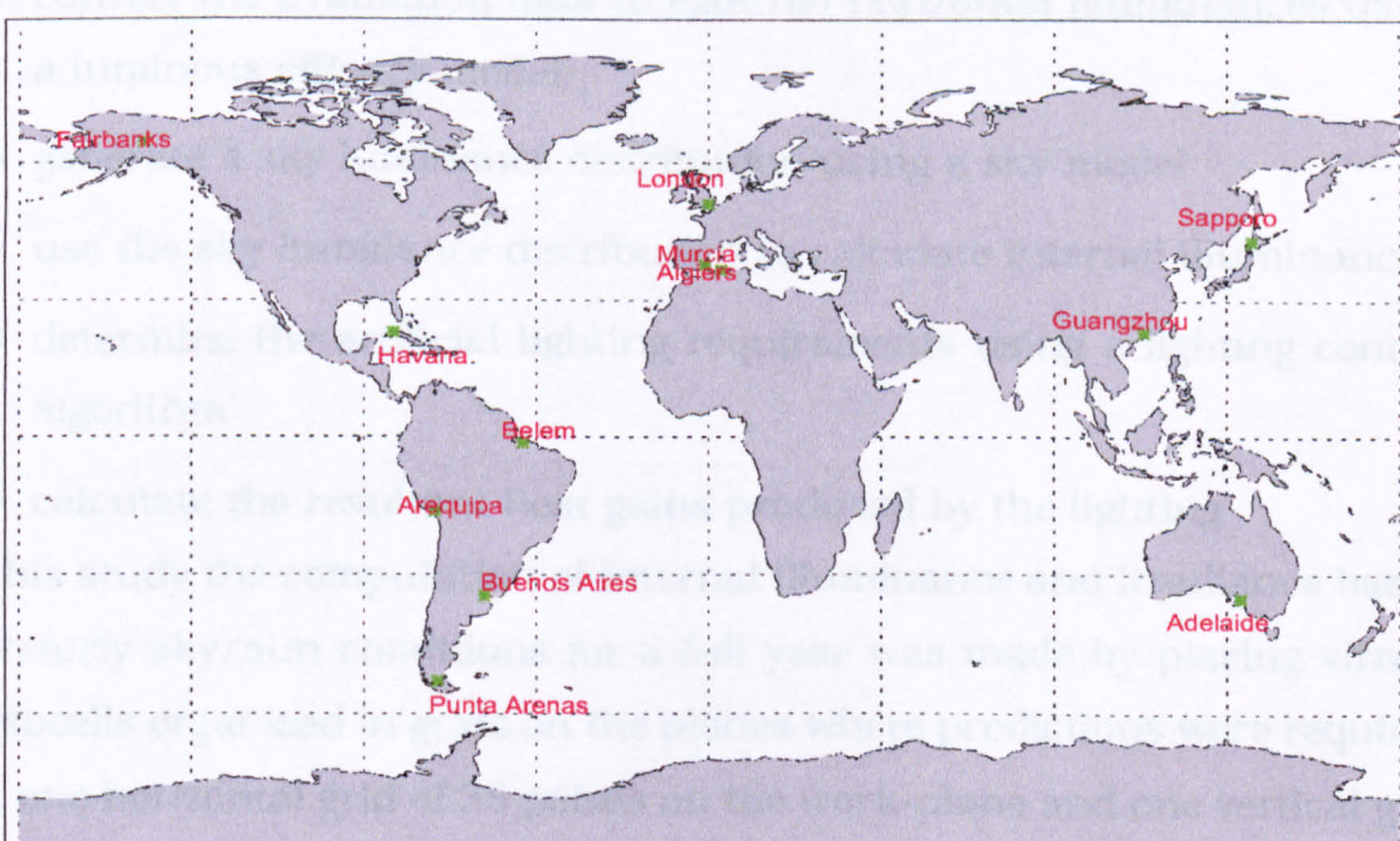


Figure 5-2 Locations of the 12 climates evaluated

5.2 Calculation procedure

The prediction of the effect of shading devices on energy consumption of non-domestic buildings uses long term evaluations i.e., annual energy consumption. Annual evaluations take account of the influence of seasonal variations of sky luminance patterns and temperatures, which can have a significant effect on energy loads (lighting, heating and cooling). For lighting loads, the more precise evaluation of the daylighting performance, the more accurate evaluation of electric lighting consumption can be performed. A combination of natural and electric lighting with control systems will cater for a range of visual environment requirements. However, for an accurate prediction based on realistic data, a full year of internal illuminances values should be calculated based on real climate data from the locale.

According to Littlefair [1992] the procedure adopted should consist of the following steps:

- obtain basic climatic data from a weather file, usually global and diffuse irradiation
- convert the irradiation data to external horizontal illuminances using a luminous efficacy model
- generate a sky luminance distribution using a sky model
- use the sky luminance distribution to calculate internal illuminances
- determine the artificial lighting requirements using a lighting control algorithm
- calculate the resultant heat gains produced by the lighting

In this study the computation of internal illuminance and irradiance based on hourly sky/sun conditions for a full year was made by placing virtual photocells organised in grids on the planes where predictions were required i.e., one horizontal grid of 36 points on the work-plane and one vertical grid of 100 points covering the window surface on the inner side of the glazing pane. The horizontal points are located where it is necessary to predict illuminance values due to different shading devices configuration whereas the vertical ones are located to predict irradiation values useful as input for the thermal model. Recall that In both cases the procedure calculates the four components mentioned previously in Section 3-3. These are the direct and indirect components of illuminance or irradiation due to the sky and the direct and indirect components of illuminance or irradiation due to the sun, respectively.

The direct components of irradiation account for the window and room configuration, external obstruction and glazing transmittance. The indirect components account for the inter-reflected irradiation, both inside and outside the room. The latter represents one of the strong assets of this methodology in the presence of external shading devices, as it accounts for the inter reflected components passing through the window-shading system. Within the shading devices configuration chosen for this experiment, some are classified as 'highly shaded' (identified as 'HS' in Figure 5-1). This type of device can occlude a high proportion of direct components (from sun and sky). However the effect of indirect components depending on climate and orientation can still be significant for an evaluation of illuminance, due to daylight and incoming irradiation through the glazing pane [Mardaljevic et al., 2006]. Predictions based upon these calculations, and a reliable climate database, can provide a solid basis for proper building energy evaluation.

Once the luminance of every point is computed, it is then possible to determine the internal illuminance for an arbitrary sky luminance distribution using arithmetic operations on matrices.

Figure 5-3 shows in detail the procedures followed by HyDiLM, making explicit how lighting simulation is part of an integrated building analysis. Both energy requirements due to artificial lighting usage and heat gains associated with the lighting system can be considered jointly with other heat gains produced within the building. Then the total internal and external gains complete the input for a thermal simulation which calculates heating and cooling loads. Finally, energy demands due to artificial lighting, together with energy consumption due to heating and cooling loads, provides the building's total energy consumption.

The flowchart in Figure 5-3 describes the procedures carried out using the automated modelling and analysis tool. Loop A in the flowchart represents the re-calculation of DCMs (Daylight Coefficient Matrices) for every shading design alternative (i.e., eight altogether).

The hourly solar irradiation (global horizontal and direct normal) and ambient temperature data from weather files (data taken from Test Reference Year database or the United States' equivalent, TMY) for all the twelve locations were loaded. In conformance with the steps described in Section 4.3.3 the daylight hours, i.e. where the irradiation is greater than zero, at each location was first calculated. For every daylight hour in the year at every geographical location (Loop B in Figure 5-3), the sky and sun luminance and radiance distributions were generated for four azimuth orientations of the office model. These orientations started from south and were incremented clockwise by 90° at a time in order to cover a complete 360° azimuth rotation (Loop C in Figure 5-3). Then, the internal vertical irradiance inside the window glazing pane at 100 calculation points and the internal horizontal illuminance at 36 calculation points were derived.

It should be observed that the data obtained from these procedures were a total of **4** (components of illuminance derived from DCs) x **4300** (average number of daylight hours) x **36** (calculation points on the horizontal workplane) x **4** (orientations) x **12** (climate files) = 29.7 million illuminance values. Moreover, there were **4** (components of irradiance derived from DCs) x **4300** (average number of daylight hours) x **100** (calculation points on the window plane -vertical-) x **4** (orientations) x **12** (climate files) = 82.5 million irradiation values. In total 112 million data values were derived in near real-time from one set of calculated daylight coefficients. This demonstrates the efficiency of the daylight coefficient approach in this implementation. Furthermore, for this application, the DCs - Daylight Coefficients - calculation was made for all the 136 points in the same run in scripts which

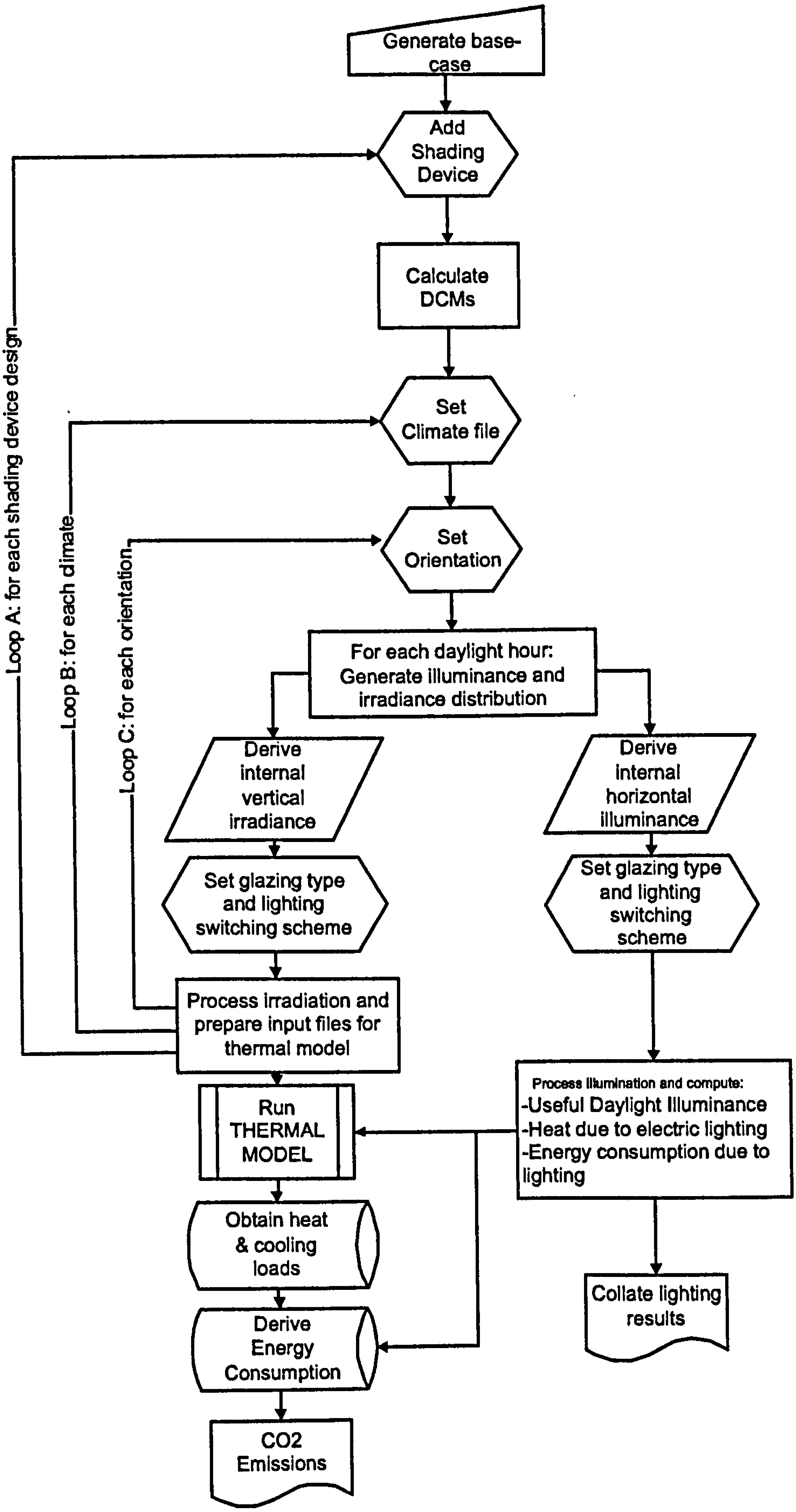


Figure 5-3 Outline of calculation procedures

included the step for the addition of the shading devices to the base-case model (Loop A in Figure 5-3). This is to say that the whole process was repeated eight times for the different shading alternatives analysed. Subsequently IDL's (Interactive Data Language) capabilities allowed the use of data from matrices to derive illuminance and irradiation values, i.e. the values were derived using 36 or 100 out of 136 for illuminance and irradiance values respectively.

Up to this stage, the consideration of daylight or irradiance values was made taking in account the number of hours 'when the sun was above the horizon', this is to say, when irradiation or daylight were available. This number of hours varies depending on the latitude, and it has been alluded to previously as an average of 4300 hour. A whole year has 8760 hours (24 hours per day by 365 days), therefore, hours of darkness were added in correct sequence to give a full year of data i.e., 8760 hours.

5.3 Evaluation criteria

Following the application of the proposed modelling technique -HyDiLM-, sets of simulation results are available for an energy building analysis. Criteria for the evaluation of external shading devices can encompass a wide variety of interest, however, within this thesis, two main interests were followed: qualitative and quantitative ones.

Amongst qualitative criteria, the quality of the illuminated environment was considered of major significance since one of the outcomes from the literature review was users' preference for daylighting due to its quality matching closely with human visual response [Li et al., 2001] and generating sensations which lead to an improvement in attendance and productivity in the non-domestic sector [Tonello, 2001].

With uniformity across the work plane an important parameter, promoted to guarantee the space will appear well lit, recommendations by the CIE [CIE, 1988] and national institutions in France [A.F.E., 1993], United Kingdom [CIBSE, 1994] and Argentina [IRAM, 1974] agree on this. However, it has been argued that the uniformity of daylight distribution cannot be as restrictive as it is for the field of artificial lighting [Fontoynont, 2001]. Here the analysis is centred in 'objective' qualitative parameters and, therefore, the feasibility of uniform lighting in daylit rooms is based on the Useful Daylight Illuminance concept.

The illuminance values, apart from aiding the calculation process of estimating electric lighting loads, can give information about the quality of the visual environment due to the windows-shading system's design. The assessment possible to be made thanks to UDIs quality of the illuminated environment is closely related to the UDI assessment tool (Section 2.3.3) as it gives an indication about the illuminance level throughout working hours and uniformity across the work-plane. The original UDI formulation [Nabil, 2002] was thought to represent the percentage of working hours when daylight illuminances in the 'core' of the office area were within the range considered 'useful'. However, for the purposes of a more detailed analysis of the effect of external shading throughout the work-plane, a point by point calculation was performed here as it was presented lately by the author [Nabil et al., 2006].

With respect to quantitative criteria, a building energy performance approach has been adopted through energy consumption calculations (due to heating, cooling and artificial lighting) and their influence on carbon emissions. The percentage of occurrences of events where the level of lighting on the work plane is satisfactory for office tasks is used for the determination of the energy consumption for electric lighting according to two different switching schemes which are explained in depth later in Section 5.3.3. Irradiation coming through the window-shading system added to internal gains are used to determine loads due to heating and cooling. Further calculations can estimate the annual energy consumption demands and carbon emissions[17] due to the use of external shading

17. Carbon Emissions can be estimated where data about the energy production process is available.

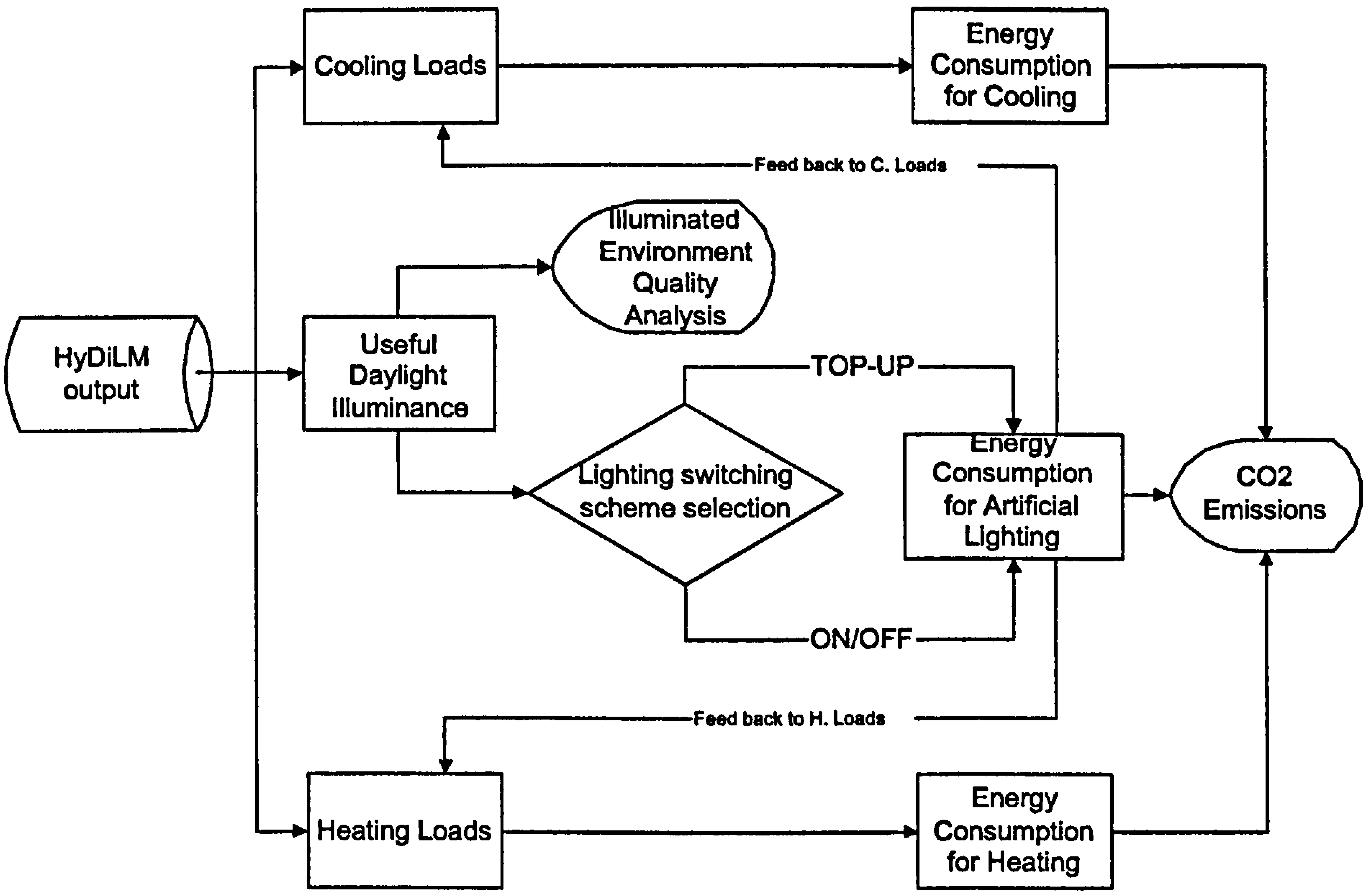


Figure 5-4 Evaluation scheme

devices. This section presents the results of using the HyDiLM to evaluate alternatives of shading devices design from both time varying illuminances and irradiation values together with energy loads and carbon emissions. In order to show the way results can be analysed, two climates out of the twelve used for predictions were selected and their results analysed. Results for other climates are stored in Annex B.

A proposed structure to evaluate the results is presented in Figure 5-4, where the output from HyDiLM are:

- Illuminance values expressed as UDI (Useful Daylight Illuminance). These are used for two purposes i.e., a *qualitative analysis* of the illuminated working environment through the uniformity possible to achieve due to different shading devices design for each orientation and a *quantitative analysis* of the energy consumption due to artificial lighting under two different switching schemes (ON/OFF and TOP-UP defined later in Section 5.3.3).

- Heating and cooling loads are used for the estimation of energy consumption due to seasonal efficiency of heating and cooling systems. The process includes also the part of heat dissipated by the artificial lighting system with its switching scheme.

Therefore, the evaluation includes Daylight Illuminated Environment Quality, the Overall Energy Consumption which comprises energy consumption due to lighting, cooling and heating and the effects on CO_2 emissions based on the composition and efficiency of the energy resources.

5.3.1 Daylight and Illuminated Environment Quality

As discussed in Chapter 2, traditional daylighting metrics not accounting for the variability of natural light (i.e. time varying sun and sky conditions, orientation effects, etc.) are not considered - in this thesis - for an evaluation of the quality of the visual environment in non-domestic buildings using shading devices. The new metric, UDI (Section 2.3.3), has been adopted following the latest approach presented by its author to assess daylight in multi-storey office buildings [Nabil et al., 2006]. Hence, UDI values are considered for every point throughout the working plane, also, the three parameters of UDI defined in this approach are estimated:

- 'UDI achieved' when the range of illuminances considered useful are between 100 lux and 2000 lux.
- 'UDI fell-short' when the level of illuminances is lower than 100 lux.
- 'UDI Exceeded' when illuminances exceed the top value of the achieved range: 2000 lux.

These three parameters are obtained from the values of UDIs considering one cross section of the room analysed. For the geometry that is under analysis, one of the central rows of virtual photocells represents 6 out of the 36 possible UDI values throughout the work-plane. Because the grid used has an even number of rows, the row selected is not exactly centrally located but is a half module displaced to one side. However, for the purposes of this study, it was considered equally representative.

These two elements can provide substantial information of the daylight performance, while the values of UDI for every virtual photocell throughout the space can inform about the degree of uniformity predicted for the whole year. The three parameters analysed simultaneously can synthesize the reasons why a better level was not achieved i.e., either because the locale and shading device design provides an excess of daylight or because it falls short (Figure 5-11).

Along with these two parameters, a novel index based on the UDI concept is presented here. This describes the general quality of daylight in the room, giving an indication of the propensity to uniformity on the work plane throughout the working year. To obtain the 'propensity to uniformity' within a daylit room a ratio between the 'minimum value' of UDI achieved at any point throughout the work plane and the 'mean value' of UDI across all the considered points should be estimated. This gives an index between zero and one distinguishable with the concept of Mean Uniformity across the working plane. However, because it works with percentage of occurrences within a range -considered useful- rather than illuminances levels, it avoids extreme values, therefore instead of providing an instant appreciation of uniformity i.e., it shows the propensity of that configuration to uniformity throughout the working year.

The expression for calculation is as follows;

$$PU = \frac{MinUDI_{achieved}}{MeanUDI_{achieved}} \tag{5-1}$$

where:

PU is the propensity to uniformity index

MinUDI $_{achieved}$ is the minimum percentage value achieved across the work-plane throughout the working year.

Mean UDI $_{achieved}$ is the mean value considering all the values of UDI achieved across the work-plane throughout the working year.

The index proposed in this work is an indicator of merely 'high' and 'low' propensity of daylight uniformity values. However, further studies can determined more precisely a scale of acceptable values related to visual tasks and sensitivity. Daylight uniformity ratios have been recommended on a desk in accordance with the sensitivity of the eye (minimum ratio = 0.7) [Velds, 2000]. This suggests that, for an entire room 'reasonable' ratios are still necessary to be proposed as uniformity thresholds to describe the general quality of daylit rooms [Fontoynont, 2002].

5.3.2 Thermal Performance and Energy Consumption

In this research, thermal modelling has been addressed by a straightforward nodal model which has been described in detail in Section 3.3. The thermal model allows the prediction of seasonal energy consumption, effects of thermal mass and likelihood of passive solar gain or exclusion. Outputs of the thermal model are heating and cooling loads for each of the twelve location selected, eight different shading devices' design and the four main orientations. The calculation procedures have been outlined in Figure 5-3 and explained in detail throughout Section 5.2.

Figure 5-5 presents a scatter plot between cooling loads values for the 384 cases studied in the experiment representing 8 different shading devices scenarios, in 4 orientations for 12 climates worldwide and the mean solar gain through the window-shading system. The plot shows a tendency whereby higher values of total solar gain correspond to higher cooling loads, however the relationship between cooling loads against solar gain does not show as strong correlation as would be expected following shadings influence in solar gains. This observation can be explained by understanding that irradiation entering the space can vary significantly but, in order to originate cooling loads, is summed to other internal gains (due to equipment, people and lighting) and external gains (infiltration), with the

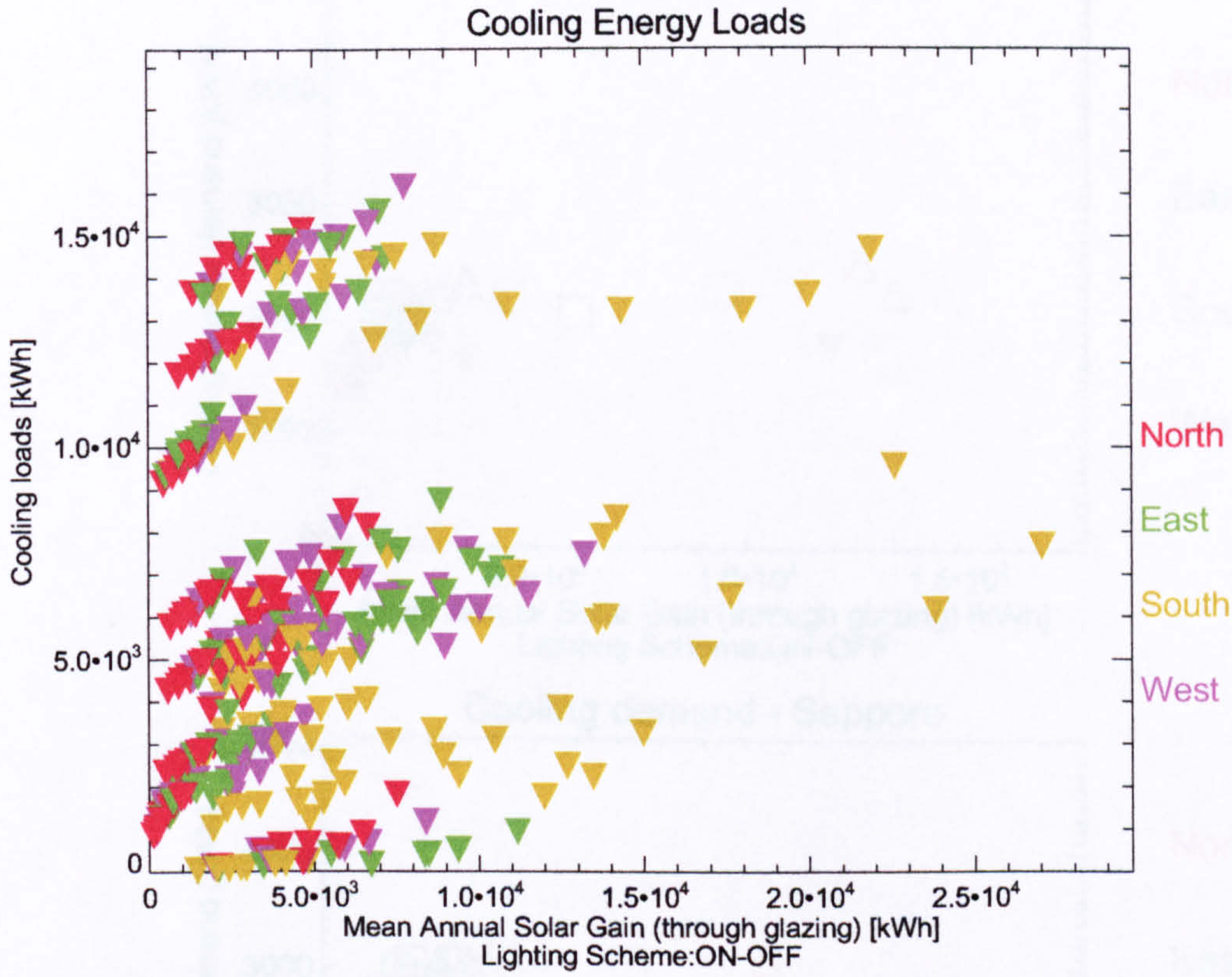


Figure 5-5 Cooling vs Solar gain

other gains remaining with almost no variations through different cases. The complex processes of interaction between surfaces and air at external conditions (temperature and humidity) coming as infiltration or ventilation into the room can cause loads not to grow in the same proportion as the irradiation values.

Figure 5-6 shows two different climates (London, UK and Sapporo, Japan) with shading devices grouped in three different designs : horizontal lovres (represented by small shaded triangles), vertical louvres (represented by squares)and light-shelfs(represented by big triangles). Here, it is possible to appreciate in more detail that there is no significant sensitivity between a reduction of solar gains and the cooling loads. In both cases the reduction produced by a horizontal louvre at 45 degrees shows significant compared

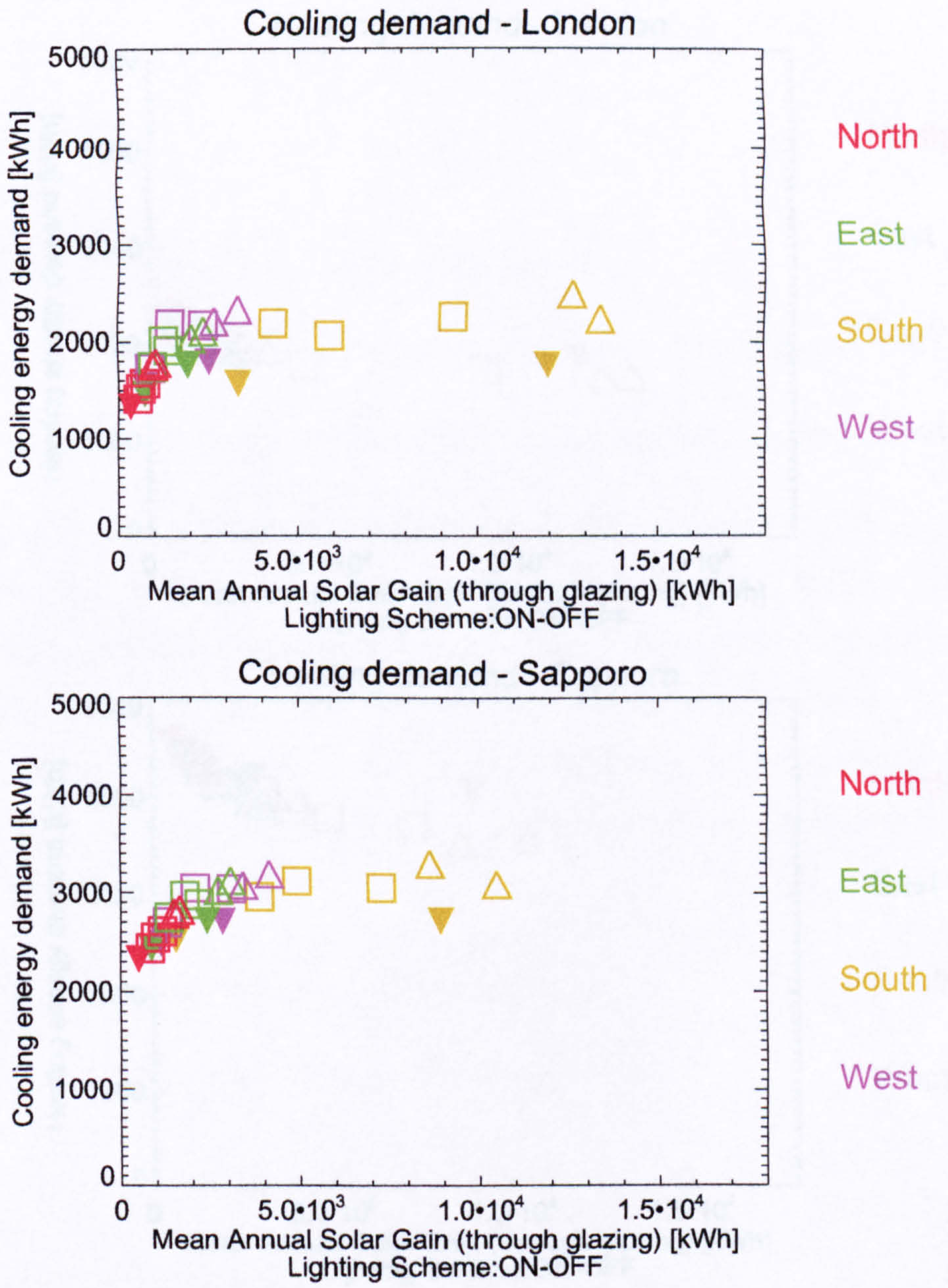


Figure 5-6 Shading Devices effects on cooling in two different climates

with horizontal 0 or any of the cases of light-shelves, however, cooling loads do not show a comparable result. Figure 5-7 shows the effect of shading devices in heating loads for the same climates, again the sensitivity is low and even with a low shaded option as light-shelves are, a reduction in heating loads is not significant.

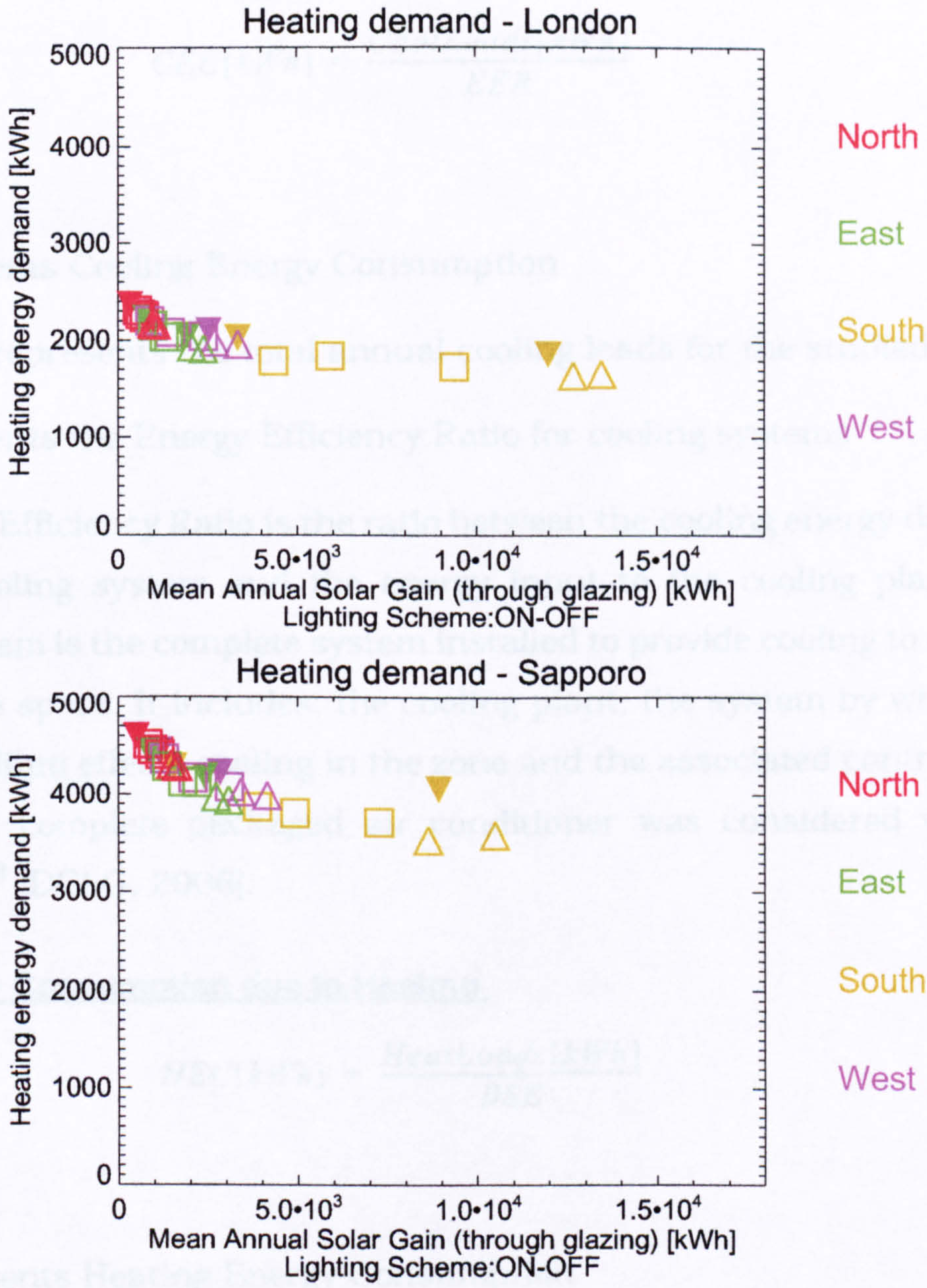


Figure 5-7 Shading Devices effects on heating in two different climates

Values of energy loads are used here for the estimation of energy consumption due to seasonal efficiency of heating and cooling systems in order to analyse each requirement in context with other energy demands. Hence, it was considered that energy loads due to cooling and lighting were powered by electricity, heating was considered to be powered by natural gas. To obtain energy consumption the following expressions were used:

Energy Consumption due to Cooling

$$CEC[kWh] = \frac{CoolLoads[kWh]}{EER} \tag{5-2}$$

where:

CEC represents Cooling Energy Consumption

Cool Loads represents the total annual cooling loads for the studied room

EER represents the Energy Efficiency Ratio for cooling systems

The Energy Efficiency Ratio is the ratio between the cooling energy delivered into the cooling system and the energy input to the cooling plant. The cooling system is the complete system installed to provide cooling to comfort levels to the space. It includes: the cooling plant, the system by which the cooling medium effects cooling in the zone and the associated controls. For this case a complete packaged air conditioner was considered with an EER=1.80[18] [DCLG, 2006].

Energy Consumption due to Heating

$$HEC[kWh] = \frac{HeatLoads[kWh]}{BSE} \tag{5-3}$$

where:

HEC represents Heating Energy Consumption

Heat Loads represents the total annual heating loads for the studied room

BSE represents the Boiler Seasonal Efficiency

The Boiler Efficiency is the ratio between the energy delivered by the water as it leaves the boiler to supply the heat emitters and the energy in the fuel delivered to the boiler expressed as a percentage. It excludes boiler and auxiliary controls energy, pumps and ventilation or flue extraction fans. A

18. The EER value used is one of the lowest values, any other conditioner equipment would reduce energy consumption values [DCLG, 2006]

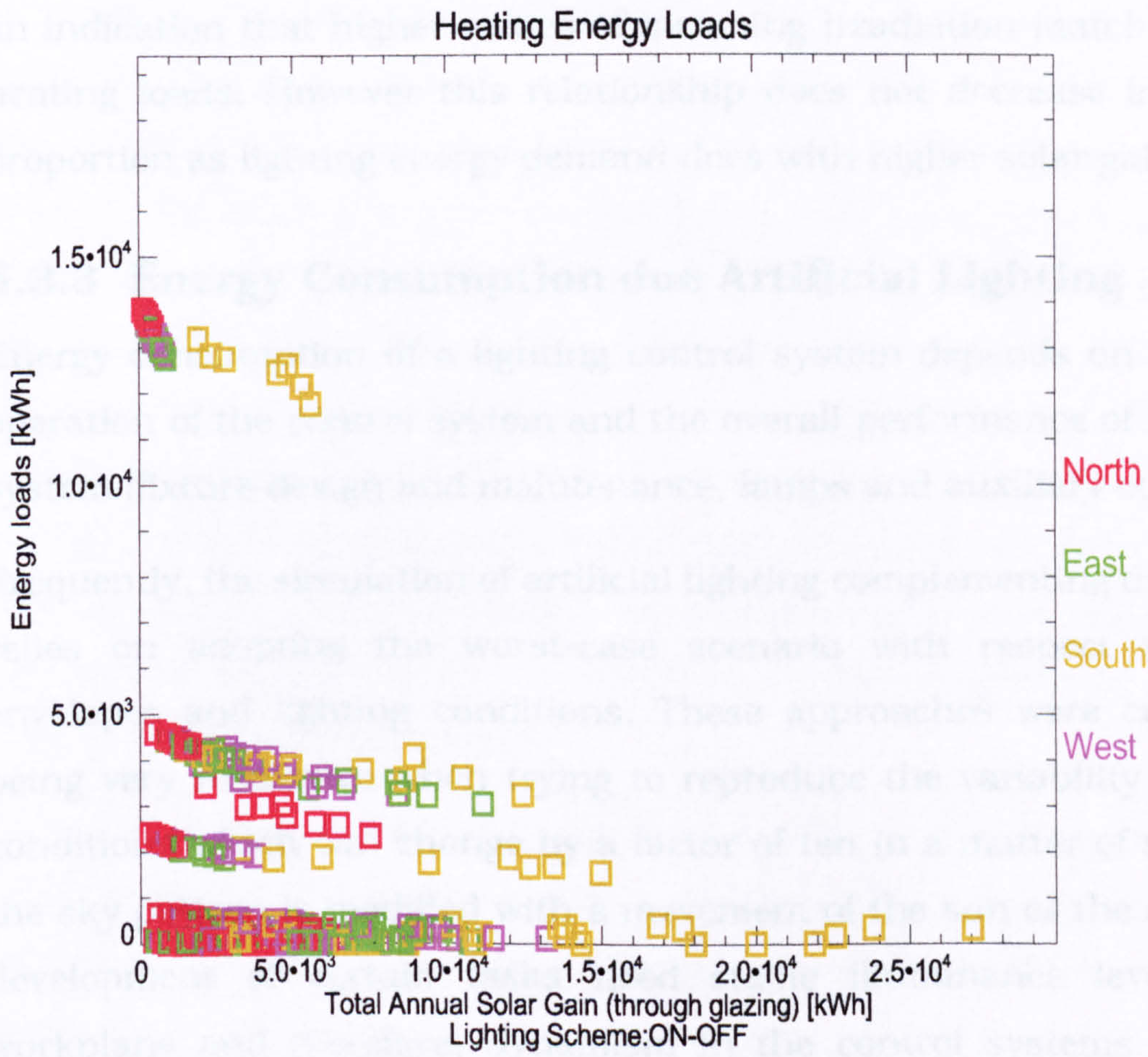


Figure 5-8 Heating demand vs Total Solar Gain

boiler meeting the minimum requirements of the boiler Efficiency Directive would have a Boiler Seasonal Efficiency of approximately 78.5% [DCLG, 2006].

It should be noted that values for boiler efficiency and energy efficiency ratio for cooling were widely used for the climates tested in the experiment. This assumption was made in order to perform a simulation in parallel 'under similar conditions', however adaptations should be made, particularly in the case of EER for cooling, as the design of the plant from one latitude to other can vary significantly and chillers performance are directly related with outdoor air temperature [Lebrun et al., 2007].

Figure 5-8 presents heating load values against total annual irradiation values for each one of the 384 cases studied. As for cooling loads, there is an indication that higher values of incoming irradiation match with lower heating loads. However this relationship does not decrease in the same proportion as lighting energy demand does with higher solar gains.

5.3.3 Energy Consumption due Artificial Lighting

Energy consumption of a lighting control system depends on the precise operation of the control system and the overall performance of the lighting system (fixture design and maintenance, lamps and auxiliary equipment).

Frequently, the simulation of artificial lighting complementing daylit spaces relies on adopting the worst-case scenario with respect to building envelopes and lighting conditions. These approaches were criticized for being very restrictive when trying to reproduce the variability of external conditions which can change by a factor of ten in a matter of seconds, as the sky pattern is modified with a movement of the sun or the clouds. The development of certain tasks need stable illuminance levels on the workplane and therefore, dynamism in the control systems to work in conjunction with daylight provision are required [Selkowitz, 1999]. Approaches to assess the lighting control system in relation to workplane illuminance levels were chosen in this work in order to produce more realistic predictions based in real climate data and dynamic control systems.

For the evaluation of energy consumption due to artificial lighting in the presence of shading devices, two different electric lighting scheme were used: ON-OFF and TOP-UP switching systems are described in this section.

ON/OFF lighting switching system

The ON/OFF lighting switching system considers that for any point in the grid at working-plane level falling below 500 lux of illuminance during working hours, a constant level of 500 lux of illuminance is provided across the work-plane by artificial means. The switching scheme was considered to be automatic and providing the same illuminance level to the whole room. As stated in the description of the room, this was considered to be a non-domestic building (offices or classrooms) and therefore, primarily fluorescent lamps were assumed for it. The efficacy of fluorescent lighting is linked to the efficacy its components: fluorescent lamps, the luminaire and the ballast. In Section 4.3.3 the lighting power density for the comparison against ESP-r was adopted from offices guidelines as 12 W/m^2 [CIBSE, 2006]. For this energy prediction fluorescent lamps of ~92 lm/W were used (which corresponds with T8 lamps currently in the market [Sylvannia, 2007]). The light output ratio (LOR) of the luminaires was taken to be 0.5, although no particular luminaire nor layout of them were selected for the experiment, this values can be deliver by different arrays of lamps and luminaires through the room.

Assuming a loss factor of ~10% due to dirt and ageing depreciation (considering an acceptable maintenance level) the average net luminous efficacy of the electric lighting system at workplane level was taken to be ~41lm/w.

$$92lm/W \times 0.5 \times 0.9 = 41.4lm/W \quad \textbf{(5-4)}$$

The final lighting power density for this scenario was 12.07 W/m^2.

A relationship between the amount of solar irradiation coming through the window-shading system and the energy consumption due to artificial lighting can be established. Figure 5-9 presents a scatter-plot with results of annual energy consumption due to artificial lighting with an ON/OFF switching scheme against Total Annual Solar Gain (solar gains passing through the shading devices and the glazing pane).

This plot corresponds to the 384 cases analysed, it shows a clear tendency for higher energy consumption when the vertical plane of the window receives less solar gain. This tendency is graphically revealed by a green line which function represents the relationship between the amount of

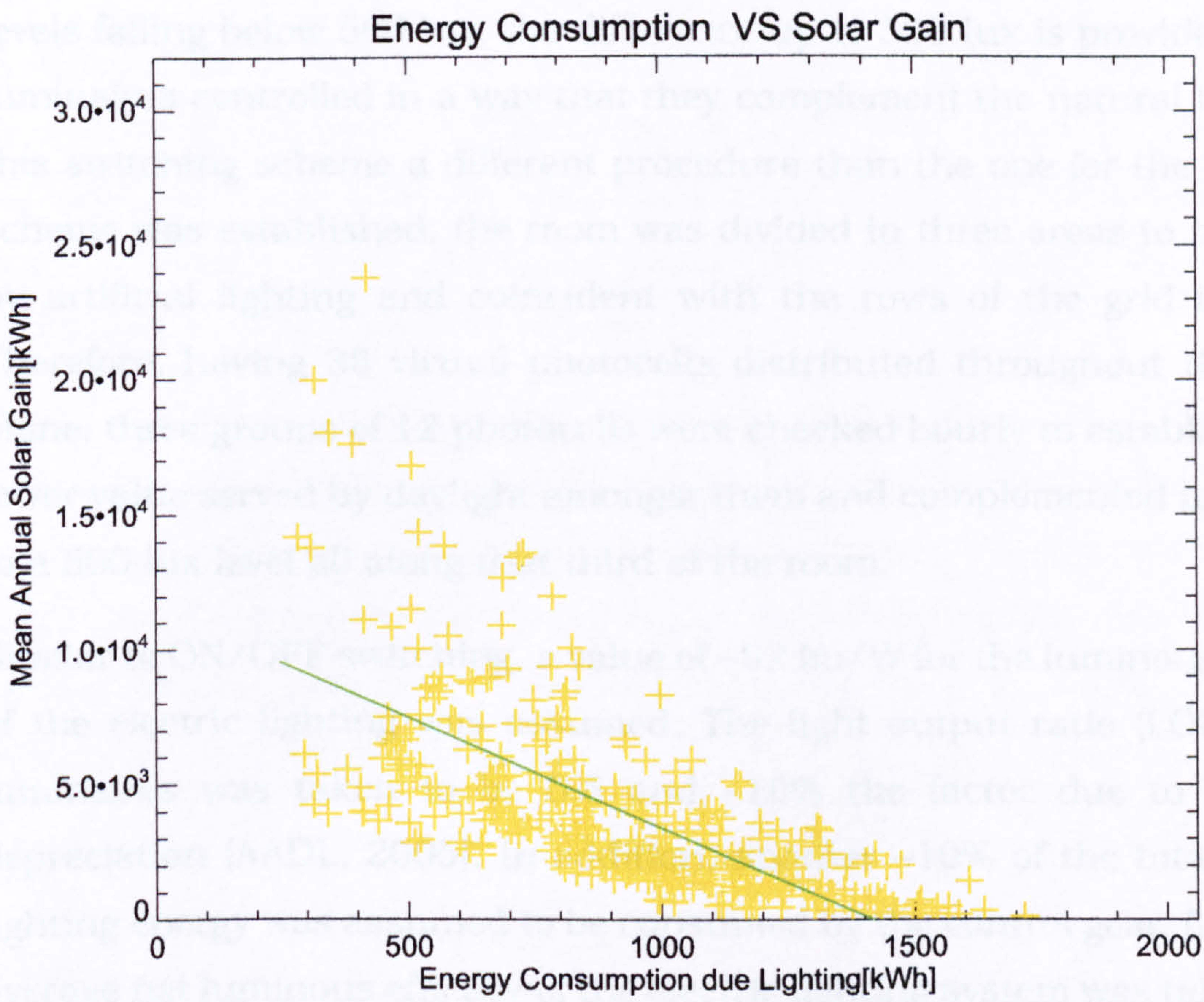


Figure 5-9 Energy Consumption due lighting (ON/OFF) vs Solar Gain

electricity due to artificial lighting and the Mean Solar Gain coming through the window-shading device system. This indicates that window-shading systems allowing high levels of solar gains should use less electric lighting. Such an affirmation contrasts with visual comfort concepts where illuminance levels count for the development of working tasks, however exceeding certain ranges or low uniformity throughout the work-plane can seriously affect the quality of the visual environment. In other words, users can use additional shading (internal shading i.e., blinds or louvres) to avoid glare and therefore, modifying internal conditions by turning artificial lights on. If is that the case, then the relationship between high levels of solar gain and low levels of energy consumption due to artificial lighting can be drastically distorted in practice.

TOP-UP lighting switching system

The other scheme used was a 'top-up' scheme, where for those daylight levels falling below 500 lux, the difference up to 500 lux is provided by the luminaires controlled in a way that they complement the natural light. For this switching scheme a different procedure than the one for the ON/OFF scheme was established, the room was divided in three areas to be served by artificial lighting and coincident with the rows of the grid by pairs. Therefore, having 36 virtual photocells distributed throughout the work-plane, three groups of 12 photocells were checked hourly to established the lower value served by daylight amongst them and complemented to 'top-up' to a 500 lux level all along that third of the room.

Similar to ON/OFF switching, a value of ~92 lm/W for the luminous efficacy of the electric lighting was assumed. The light output ratio (LOR) of the luminaires was taken to be 0.5 and ~10% the factor due to dirt and depreciation [AADL, 2005]. In addition, another ~10% of the total electric lighting energy was assumed to be consumed by the control gear, finally the average net luminous efficacy of the electric lighting system was taken to be approximately 37.26 lm/W.

The lighting power density in this case was 13.41 W/m^2, this comes from 500 lux divided by 37.26 lm/W.

This the hourly total energy consumption for each third is summed to obtain the total hourly energy consumption value of the room.

5.3.4 Overall Energy Consumption and CO_2 Emissions

The analysis of overall energy consumption in buildings in different latitudes has been the aim of various studies in the last decade, however, the consequences of energy consumption i.e., CO_2 emissions, can vary significantly from one region to the other depending on climate, technology development and natural resources available in the place. The level of CO_2 emissions is related with the efficiency and the intensive use of fossil fuel or renewable energies in the production process of primary energy. This means that each region (i.e., countries) have a different CO_2 emission factor for each one of the energy sources used to power their buildings.

Bearing all these considerations in mind, CO_2 emissions are still considered a reasonable common denominator for the evaluation of the energy consumption consequences of using different shading devices design. This study analyses some particular cases presenting energy consumption expressed as CO_2 emissions values.

Previously stated assumptions included that cooling was powered by electricity and heating by natural gas, therefore, conversion factors from energy consumption expressed in kWh to carbon dioxide emissions in $KgCO_2$ for both energy sources -electricity and natural gas- were explored within the literature for the two locales representing a heating dominated and a cooling dominated climate

$$CO_2[KgCO_2] = EC \times EF_s \tag{5-5}$$

where:

CO_2 are the Carbon Dioxide emissions in Kg of CO_2

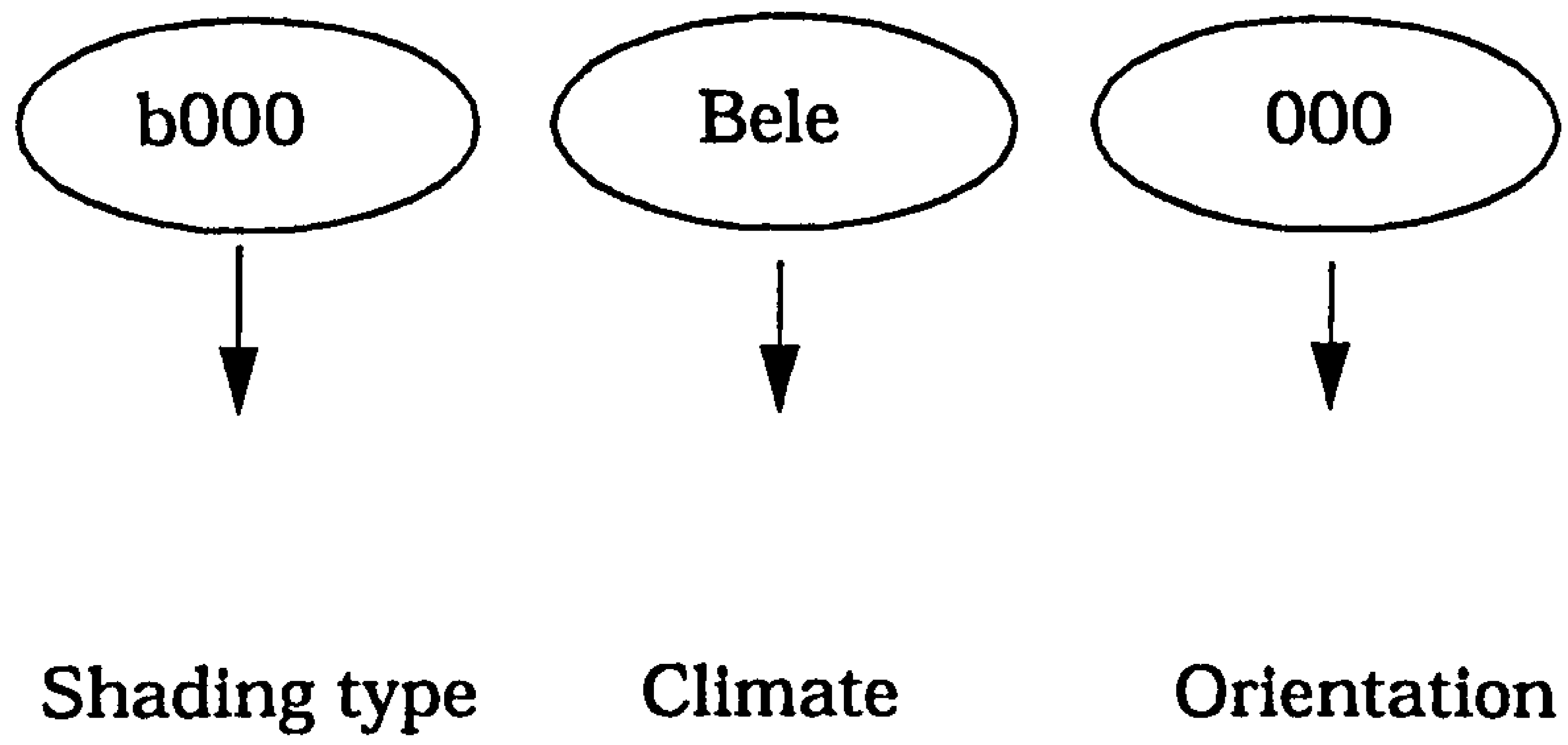
EC is the total annual energy consumption in kWh for a particular fuel.

EF is the emission factor for a particular fuel.

5.4 Study Cases

__Tropical Climate__

For every locale (climate) used for estimations listed in Section 5.1.3 a summary of daylight performance - UDI values - of all the alternatives of shading device design described in Section 5.1 for a particular orientation can be represented in a one page plot providing a prompt view of the possibilities for each design alternative. The nomenclature used for the identification of each case follows (see See “Nomenclature and Glossary” on page 117.):



Belem in Brazil (Latitude: 1.38 South-Longitude 48.48 West) a cooling dominated climate, with year round warm temperatures (all months have a mean temperature above 18 C), abundant rainfall (with annual average exceeding 150 millimetres).

In Figure 5-10, UDIs values achieved for each point where a virtual photocell is located throughout the work-plane are presented. Bottom left is the 'base-case' which has no shading devices, so this is a reference case which other cases can be compared to [19]. For the Belem- South case, it is noticeable the difference between highly shaded options like Horizontal 45 (Figure 5-1) which presents values over 80% of UDIs, informing us that during 80% of the working year the illuminances levels on the work-plane will be within the 100 to 2000 lux range.

A significant observation can be made in Figure 5-11 confirming that, for the mentioned case -Horizontal 45- there are no values exceeding and low percentages of 'falling short'. Reinforcing these observations, the propensity index for uniformity shows a high value of 0.93. Other alternative where values show an acceptable performance are the Vertical -45 and Vertical +45 where the first row of values are below the 50% of occurrences of UDIs achieved but the rest are above 80%. Between them the PU values differ, Vertical -45 shows PU= 0.49 and Vertical +45 shows PU=0.31. This value could be explained due to the higher level of excedences which climb to over

19. Note that the window in all plots is situated on the left hand side.

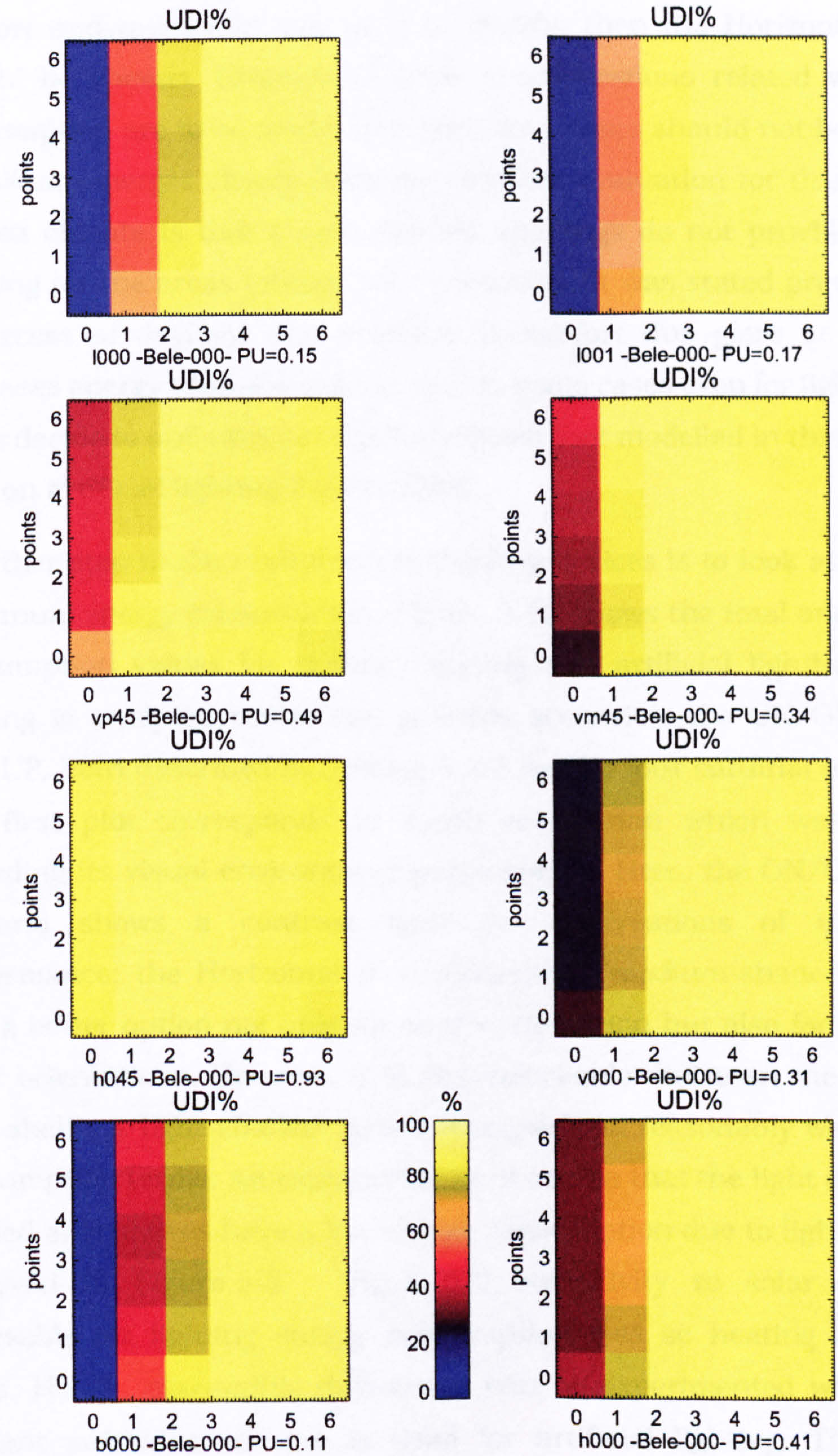


Figure 5-10 UDIs in % of the working hours for Belem - South Orientation

55% in the latter, whereas in the V-45 are still lower than 50%. These observations could lead to different decisions in the design process: if visual comfort and uniformity are used to decide, then the Horizontal 45 case should be chosen. However, if other considerations related with energy consumption are to be made, then the other cases should not be dismissed yet. What emerges clearly from the daylight evaluation for this equatorial located climate is that single element shadings do not provide sufficient shading for the areas located near a window. It was stated previously that an excess of daylight can produce discomfort due glare or heat. This increases energy loads for cooling, and in some cases even for lighting, when users decide to pull internal shadings down (not modelled in this study) and turn on artificial lighting [Nabil, 2002].

A further step in the evaluation of shading devices is to look at their effect on annual energy consumption. Figure 5-12 shows the total annual energy consumption values for cooling, heating and artificial lighting. Artificial lighting is analysed under two possible scenarios: the ON/OFF and the TOP-UP, both described in Section 5.3.3 for the four cardinal orientations. The first plot corresponds to south orientation which was examined regarding its visual environment performance. Here, the ON/OFF lighting scenario shows a contrast with the observations of the daylight performance: the Horizontal 0 -considered a 'medium-shaded' option- is now a better option not only for south orientation but also for most of the other orientations. However, it is also noticeable that even the option of a light shelf - a 'light-shaded' option -can perform reasonably well in energy consumption terms. An explanation for it can be that the light and medium shaded alternatives have a low energy consumption due to lighting and, as observed in Figure 5-5 - Figure 5-9, sensitivity to solar gains were noticeable for lighting energy consumption less so heating and cooling loads. Hence, perceptible differences can be experimented when a more efficient switching scheme is used for artificial lighting. The ON/OFF scheme does not use the full potential of daylight, the TOP-UP system takes more advantage out of daylighting as it only consumes the energy to 'fill the gap' between the daylight illuminance level and the recommended levels by the standards i.e. CIBSE.

When the TOP-UP system is applied, results differ showing the Horizontal 45 option as the lower consumption with a reduction close to a 20% less than the Unshaded case using the same lighting scheme and 17% less than the same shading device using the ON/OFF scheme. This significant difference with the ON/OFF scheme lies on the two ways that artificial lighting influences energy consumption: electricity consumption to power the lighting system and heat dispersion to the environment from lighting usage increasing cooling loads. On the contrary, for heating dominated climates, heat dispersion by lighting usage reduces energy consumption for heating.

The differences in energy consumption values then are reproduced in CO_2 emissions as can be appreciated in Figure 5-13 where the Horizontal 45 option shows the lower level of emissions and is comparable with the Vertical +45 option which was mentioned previously as one of the other alternatives when examining the visual environment performance. CO_2 emissions for Belem, Brazil, do not seem to show significant differences between the alternatives, an explanation for this can be that: first, the lack of natural gas consumption due to the negligible heating loads needed for this climate, and second the low emissions that Brazil generates for its production of electricity[20] [DOE, 2007].

Mid-latitude Marine Climate

London[21] (Latitude: 51.15North-Longitude: 0.18 West) a heating dominated climate, humid with mild winters (average temperatures of the coldest

20. Brazil high percentage of electricity from hydro origin makes its CO_2 factor one of the lowest worldwide
21. London was included for reference only since building regulations do not allow the proposed designs.

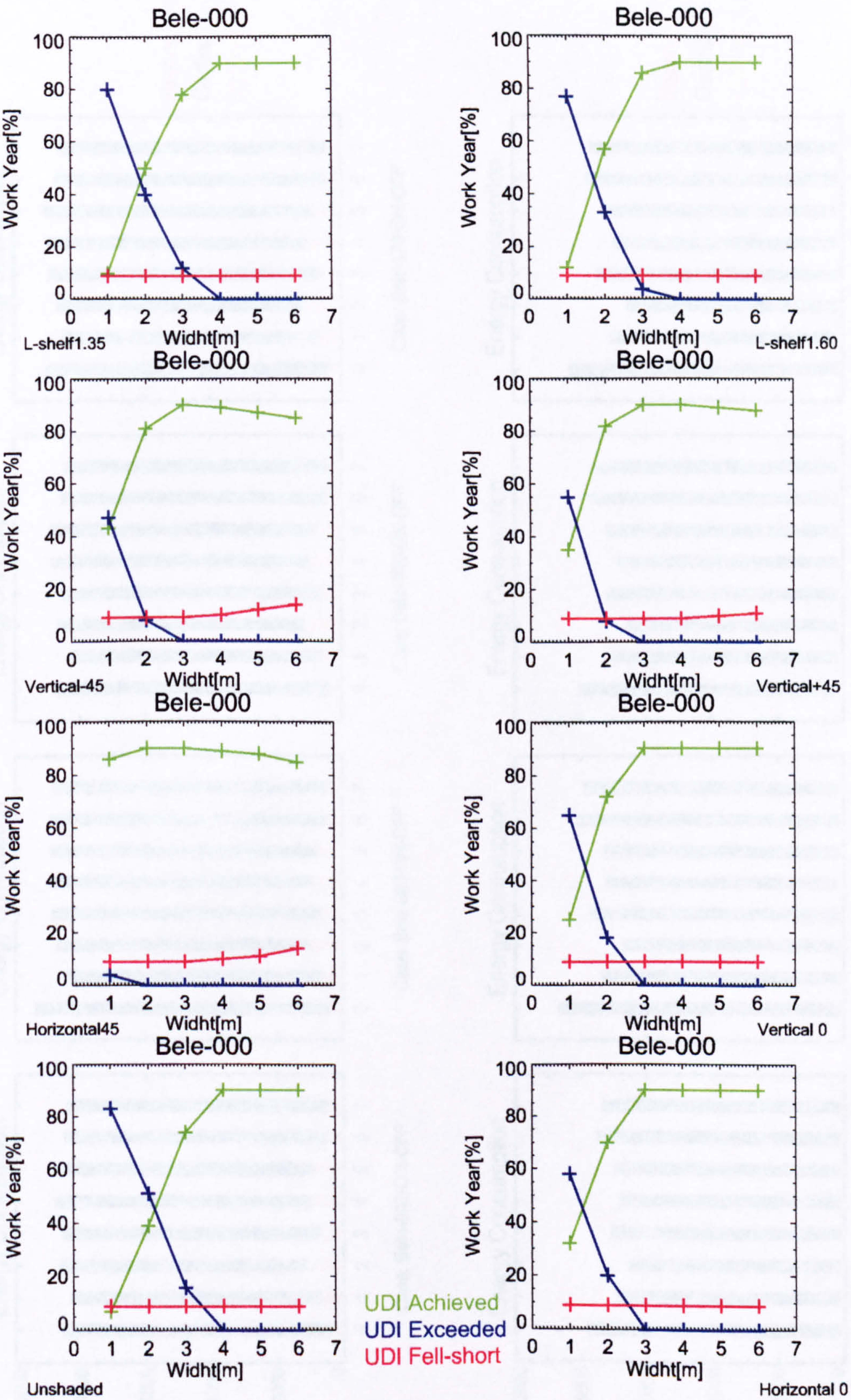


Figure 5-11 Three Parameters of UDIs for Belem (Achieved, Fell-short and Exceeded)

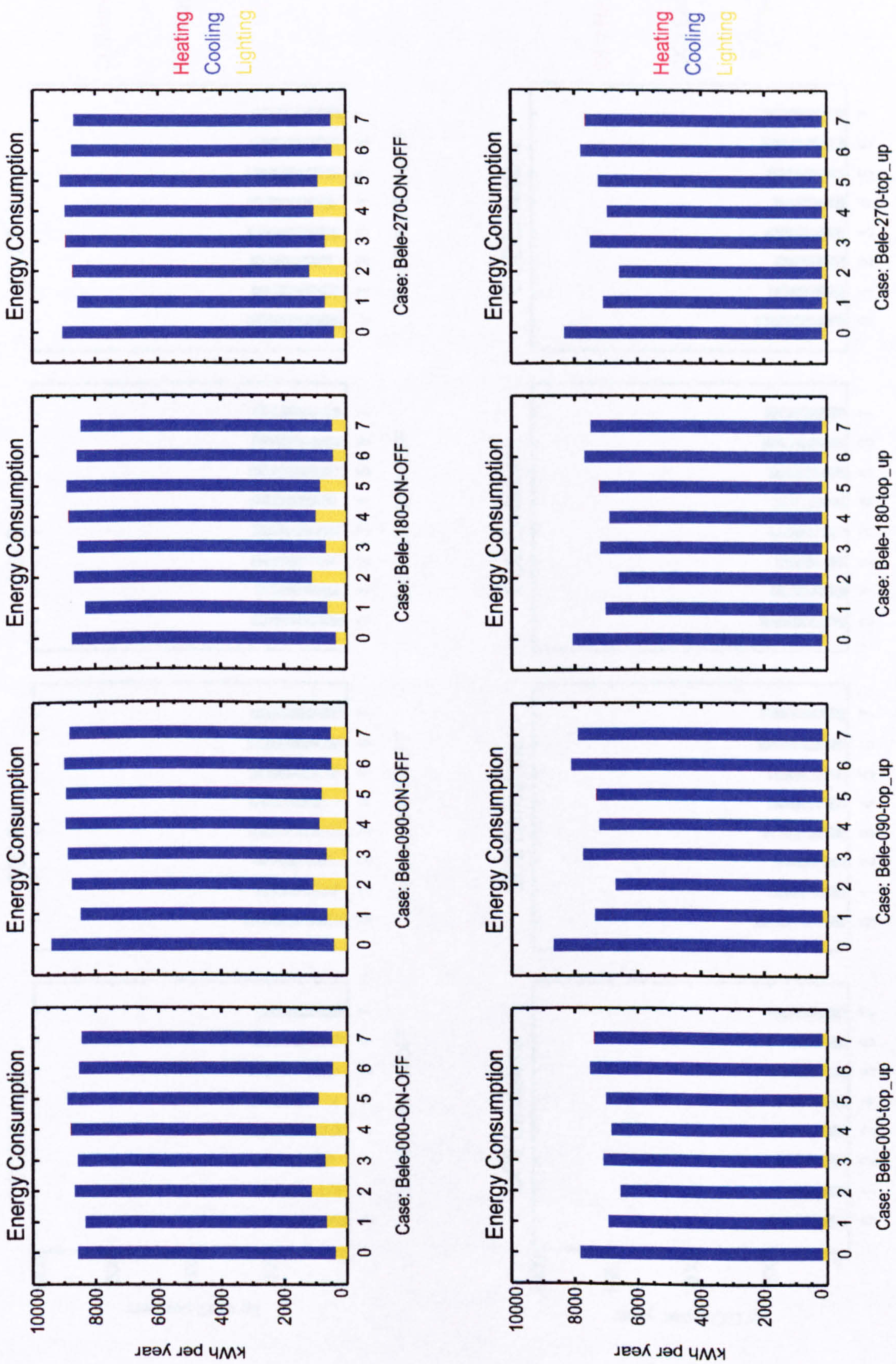


Figure 5-12 Energy Consumption for Belem

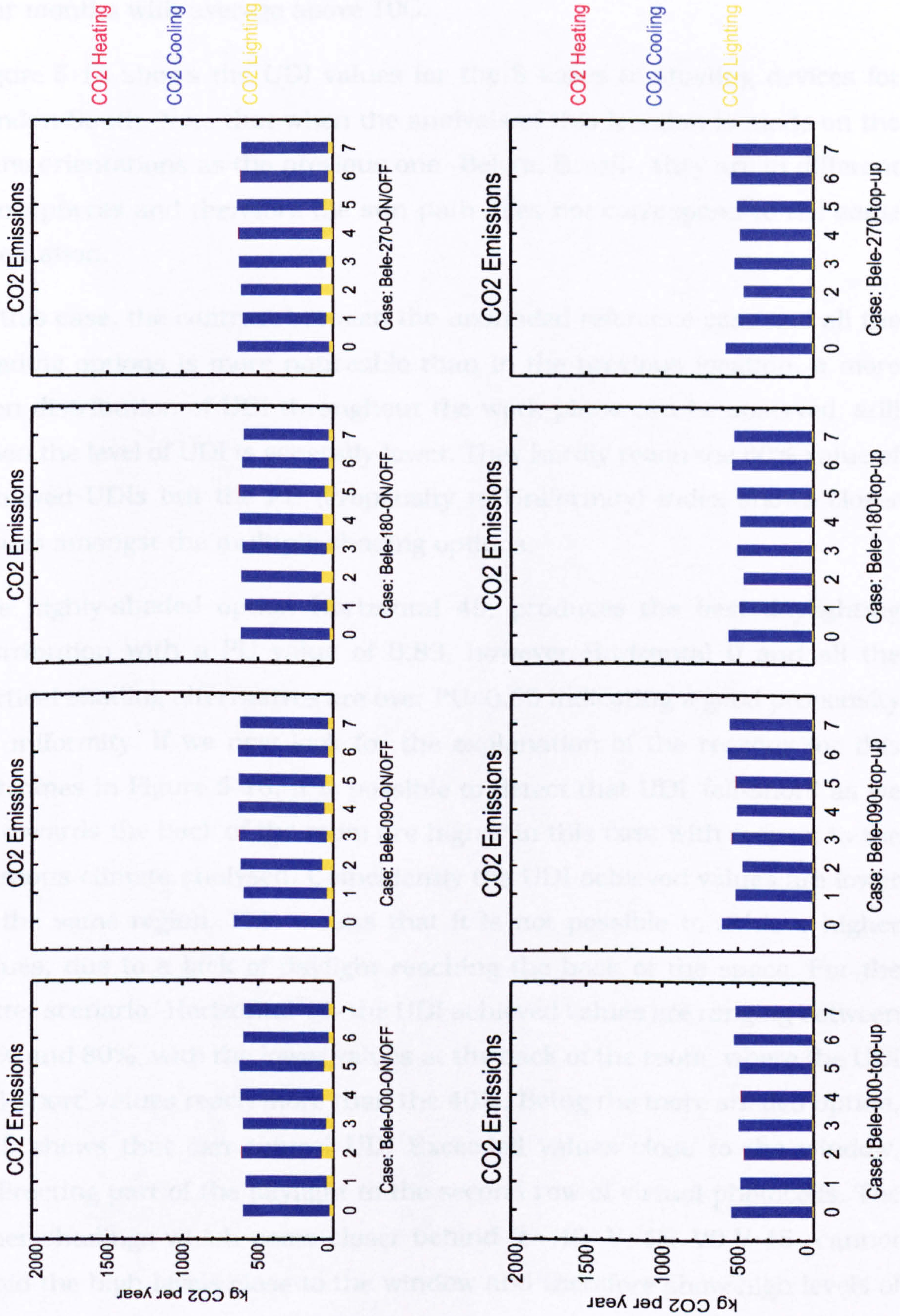


Figure 5-13 CO2 Emissions for Belem, Brazil

month below 18C and above -3C) with summers long and cool with at least four months with average above 10C.

Figure 5-14 shows the UDI values for the 8 cases of shading devices for London South. Note that when the analysis of this location is made on the same orientations as the previous one -Belem, Brazil-, they are in different hemispheres and therefore the sun-path does not correspond to the same orientation.

In this case, the contrast between the unshaded reference case and all the shading options is more noticeable than in the previous location, a more even distribution of UDI throughout the work-plane can be observed, still when the level of UDI is generally lower. They hardly reach the 80% value of achieved UDIs but the PU (Propensity to Uniformity) index shows closer values amongst the multiple shading options.

The highly-shaded option Horizontal 45, produces the best daylighting distribution with a PU value of 0.83, however Horizontal 0 and all the Vertical shading alternatives are over PU=0.50 indicating a good propensity to uniformity. If we now look for the explanation of the reasons for this outcomes in Figure 5-16, it is possible to detect that UDI 'fell-short' as we go towards the back of the room are higher in this case with respect to the previous climate analysed. Coincidently the UDI achieved values are lower in the same region. This means that it is not possible to achieve higher values, due to a lack of daylight reaching the back of the space. For the better scenario -Horizontal 45- the UDI achieved values are ranging between 55% and 80%, with the lower values at the back of the room, where the UDI 'fell-short' values reach more than the 40%. Being the more shaded option, H45 shows that can control UDI Exceeded values close to the window, redirecting part of the daylight to the second row of virtual photocells. The other shadings which come closer behind it -H0, V+45, V0,V-45- cannot avoid the high levels close to the window and therefore show high levels of UDI Exceeded i.e., around 50%. The values at the back are all above 60% of UDI Achieved values performing higher than for the H45 case.

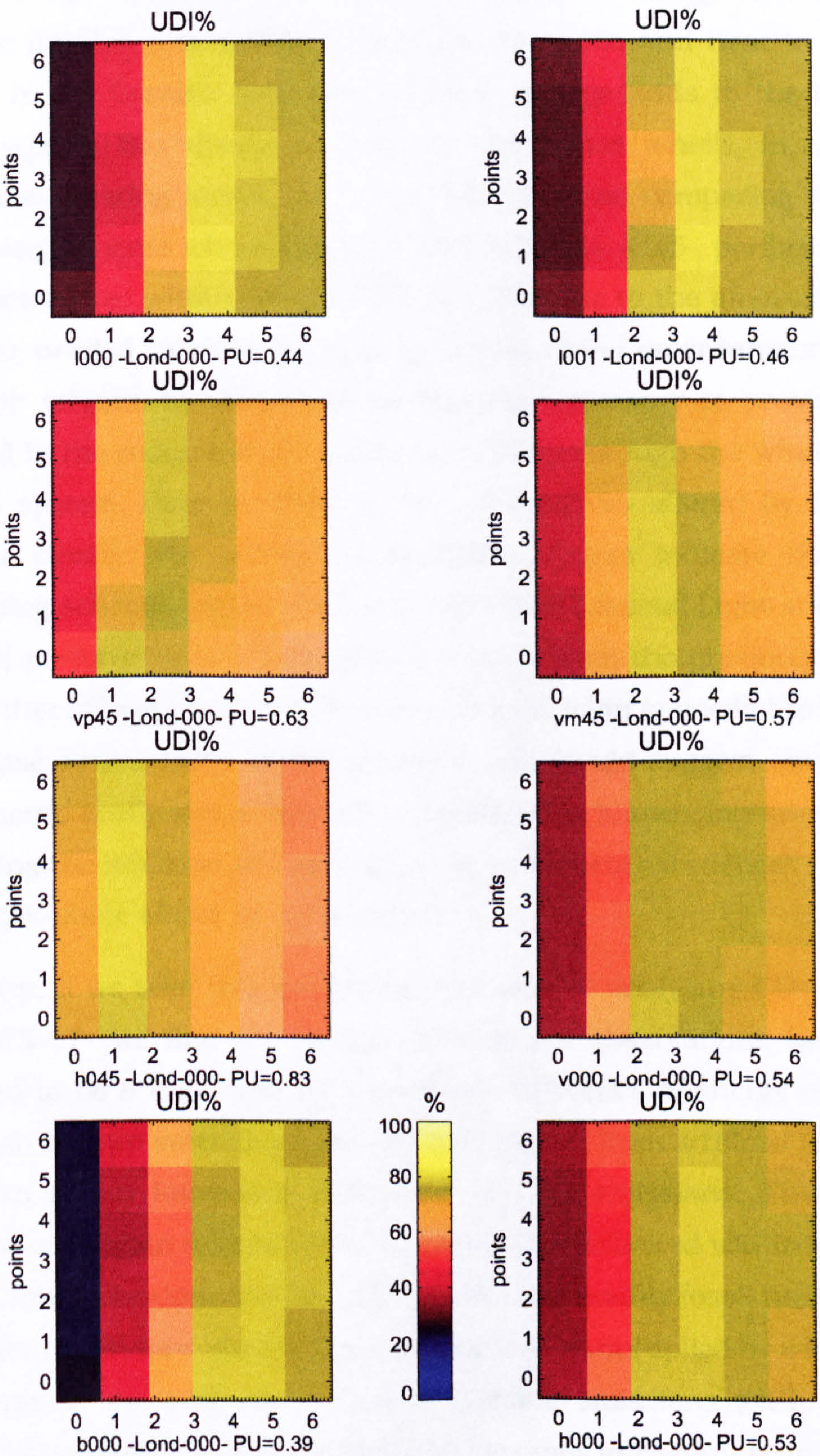


Figure 5-14 UDIs for London South

Analysing the energy demand of this case it is possible to observe, in Figure 5-15, that while in the case of Belem the energy consumption due electric lighting was adding energy consumption and heat to the cooling loads, in the London case lighting adds energy loads to the total energy consumption but dissipates heat to the space which, in this climate decreases heating loads. This is noticeable when comparing the different switching scheme where the hard shaded case -H45- performs poorly in both scenarios: within the ON/OFF scheme due to the amount of artificial lighting needed to meet the quality of the visual environment and in the TOP-UP scheme by reason of the heating necessary to provide to space caused in the reduction of irradiation coming through the window-shading device system. Here is when all the possibilities offered by the HyDiLM appear clearly: the energy consumption figures indicate that for both switching schemes either the H0 or L001 (the external Light-shelf at 1.60m height) perform equally efficiently. However from the previous analysis we know that H0 perfoms slightly better. If a decision is needed to be made on this case at this stage of the analysis, one would suggest maybe trying a parametric study about light-shelf possibilities (dimension and position) or studying the addition of internal blinds to control excedences registered in the work-plane closer to the window.

However, if we take this analysis to the step of analysing CO_2 emissions -Figure 5-17- we find an abrupt turn in the observations because what seemed to be a finding of no significant difference of energy consumption between the two switching schemes (due to heat from artificial lighting), now appears as an important difference in CO_2 emissions. This significant difference is again related to the way energy is delivered within each domain (i.e., United Kingdom and Brazil), the UK uses mainly fossil fuels to produce electricity therefore, the energy consumption is multiplied by a factor of 0.43 to estimate the amount of Carbon Dioxide emissions [NEF, 2005]. The weight of cooling and artificial lighting becomes important even in a heating dominated climate, ergo the option of lighting switching scheme regain

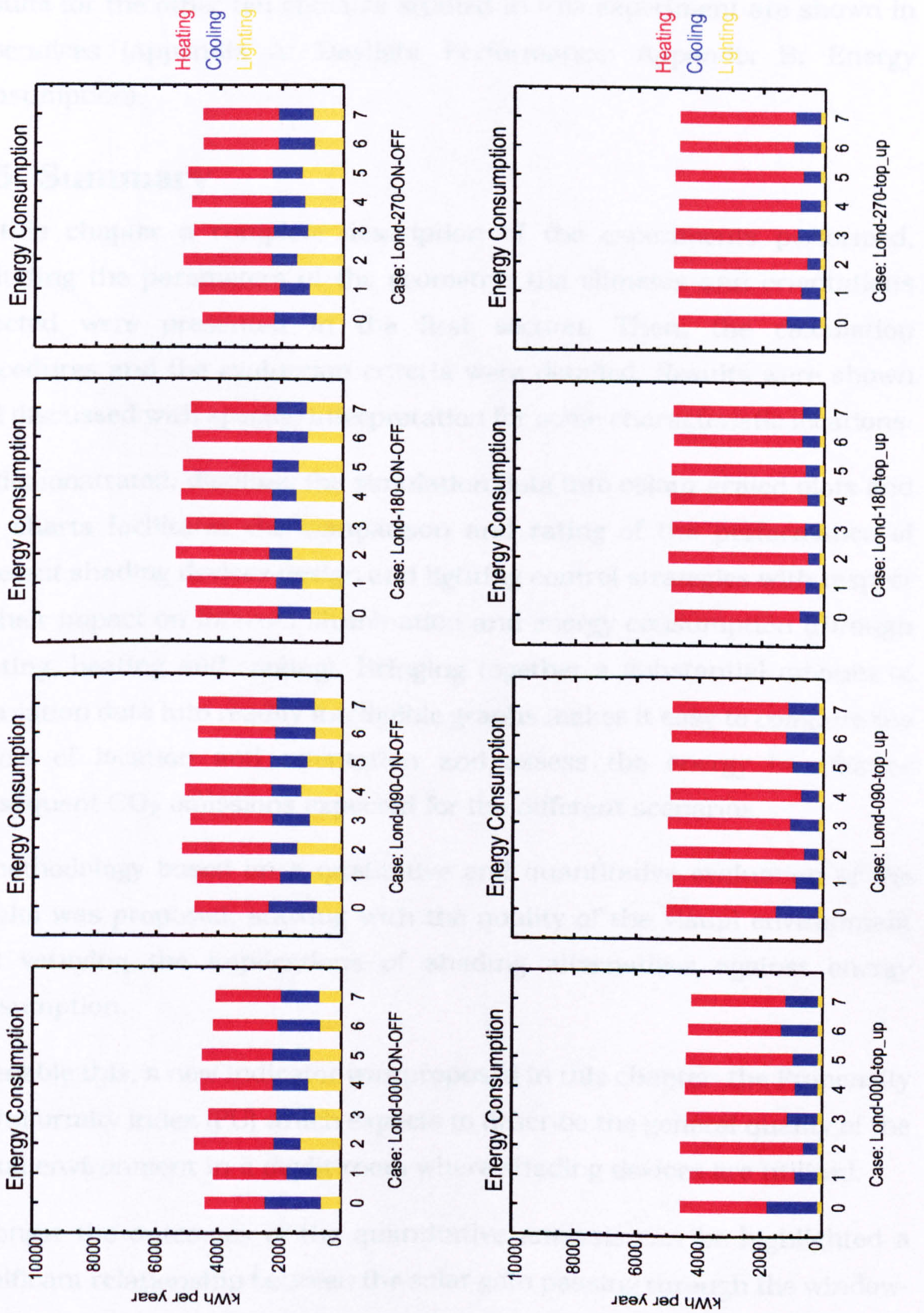


Figure 5-15 Energy Consumption for London

significance and confirms that Horizontal 45 would be a well balanced option which fulfil most of the requirements.

Results for the other ten climates studied in this experiment are shown in appendices (Appendix A: Daylight Performance; Appendix B: Energy Consumption).

5.5 Summary

In this chapter a complete description of the experiments performed, including the parameters of the geometry, the climates and orientations selected were presented in the first section. Then, the calculation procedures and the evaluation criteria were detailed. Results were shown and discussed with specific interpretation for some characteristic locations.

As demonstrated, distilling the simulation data into colour scaled plots and bar charts facilitates the comparison and rating of the performance of different shading devices design and lighting control strategies with respect to their impact on internal illumination and energy consumption (through lighting, heating and cooling). Bringing together a substantial amount of simulation data into readily intelligible graphs makes it easy to compare the effects of location and orientation and assess the energy benefits or consequent CO_2 emissions expected for the different scenarios.

A methodology based on a qualitative and quantitative evaluation of the results was proposed, starting with the quality of the visual environment and verifying the implications of shading alternatives against energy consumption.

To enable this, a new indicator was proposed in this chapter: the Propensity to Uniformity index (PU) which expects to describe the general quality of the visual environment in a daylit room where shading devices are utilized.

Amongst the outcomes of the quantitative analysis can be highlighted a significant relationship between the solar gain passing through the window-shading system and energy consumption due to artificial lighting.

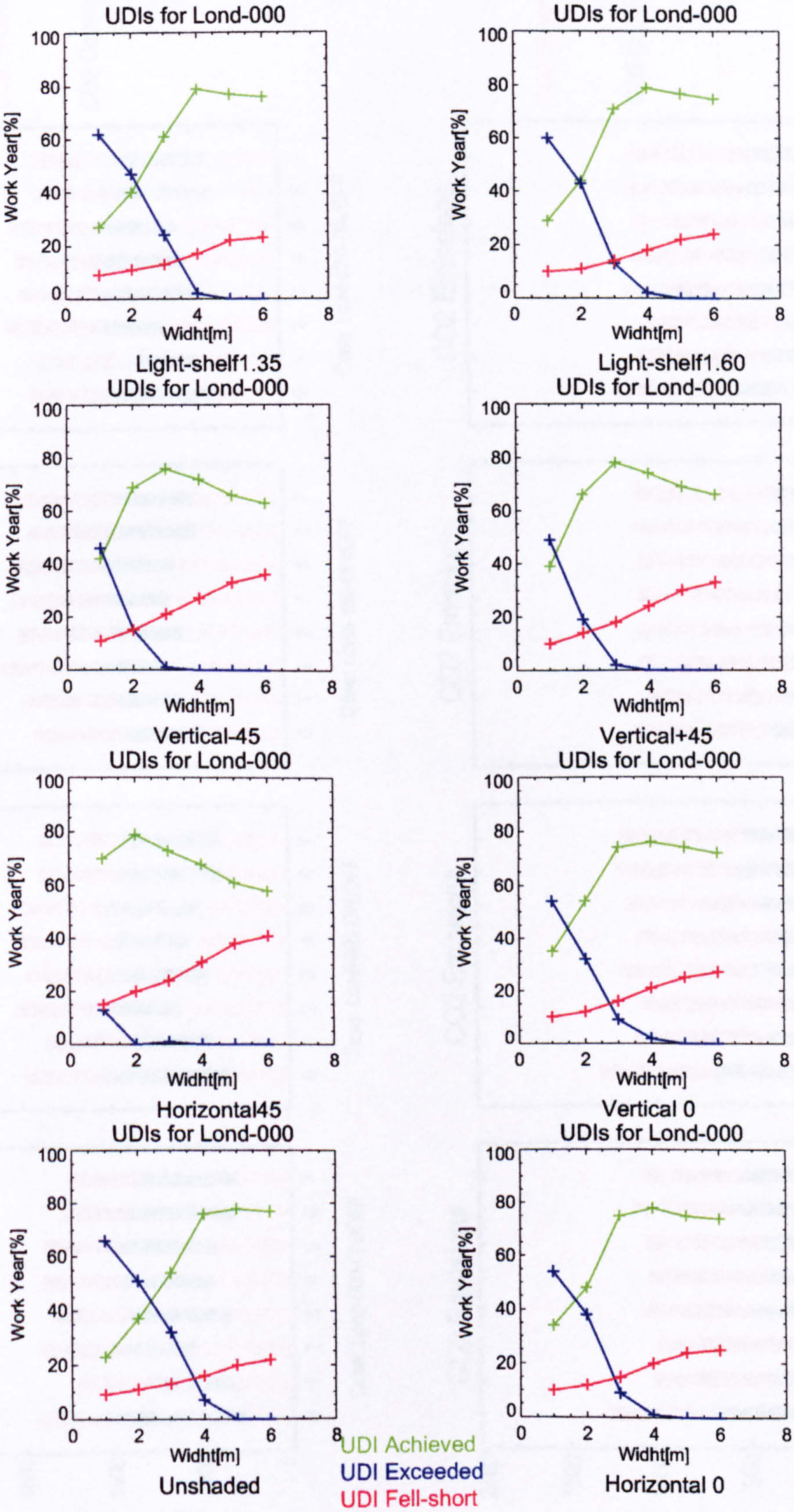


Figure 5-16 Three Parameters of UDIs for London (Achieved, Fell-short and Exceeded)

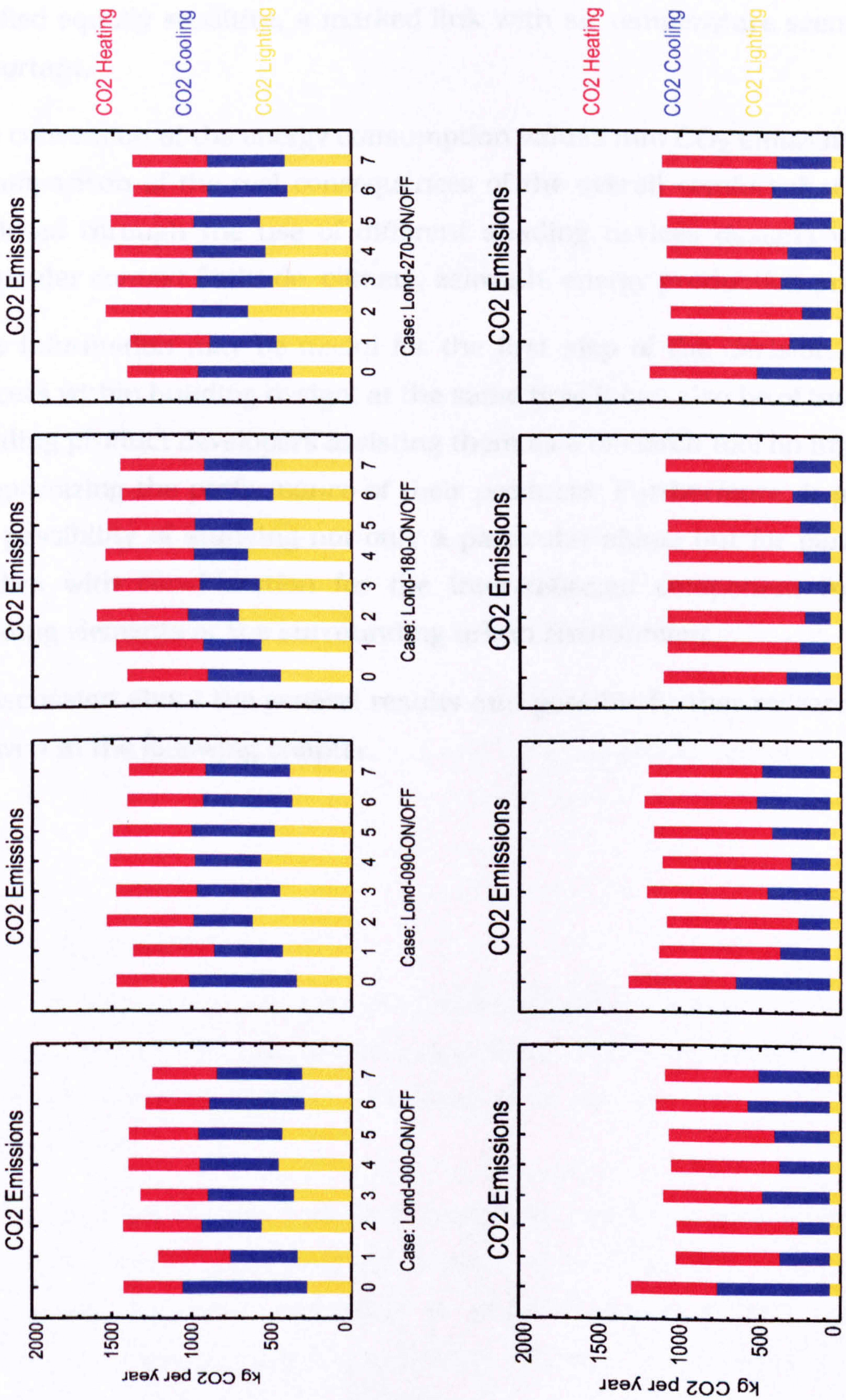


Figure 5-17 CO_2 **Emissions for London, United Kingdom**

Notwithstanding, with cooling and heating loads that relationship cannot be verified equally sensitive, a marked link with air temperature seems to be important.

The conversion of the energy consumption values into CO_2 emissions gives a comparison of the real consequences of the overall comfort that can be achieved through the use of different shading devices designs within a particular context (latitude, climate, azimuth, energy production process).

This information may be useful for the first step of the decision making process within building design, at the same time it can also be of interest to building product developers assisting them as a research tool on improving or optimizing the performance of their products. Furthermore, it provides the possibility of studying not only a particular shape but for parametric studies with consideration for the inter-reflected component from the building elements or the surrounding urban environment.

A discussion about the general results and possible further research work is given in the following chapter.

Chapter

6 Discussion and Conclusions

"Architecture begins where engineering ends"

WALTER GROPIUS (1883-1969)

6.1 Summary

The main aim of this research work has been to devise a methodology which can integrate daylight and thermal analysis to assist the complex process of designing an energy conscious building while also meeting users' comfort requirements.

A hybridization of two validated modelling programs was designed to provide an expert predicting tool capable of performing a wide range of simulations, including variations on shading device designs, climates, orientations, dynamic lighting switching schemes and building materials densities. In order to test its capabilities the new tool was compared with a recognised existing thermal model, performing acceptably.

First a review was carried out of the current best practices as promoted by regulatory bodies regarding the environmental sustainability of building, followed by an account of existing daylight and thermal modelling techniques as well as building elements providing solar shading or solar control (Chapter 2).

Based on the findings from this review, a hybridization based on two existing techniques was proposed, in order to meet the current demands in the field of quantitative and qualitative assessment of solar shading elements in buildings. The fundamentals of the modelling programs involved in the new tool were described and their implications in the whole process analysed (Chapter 3).

The design of the hybrid program was developed, with a detailed description of its application to a 'base case' given. Additionally, an inter-model comparison was performed against a widely used and validated calculation tool from the building modelling sector (Chapter 4).

A demonstration of the hybrid model, applied to external shading devices on offices of different orientations and various climates, was presented. Also, a scheme for the evaluation of energy performance, and the quality of the illuminated environment of non-domestic buildings with external shading devices, was introduced (Chapter 5). Furthermore, the design of automated light-switching implications on associated carbon dioxide emissions were also investigated.

6.2 Conclusions

The findings obtained in this study can be outlined as follows:

The consideration of shading as an integral part of fenestration system design can lead to a better energy performance within the non-domestic buildings sector. Close attention being paid to climate and orientation in shading devices design can improve significantly both the quality of the illuminated environment and the achievement of thermal comfort requirements.

An automated modelling and analysis tool, which involves custom-written programming routines and the adaptation of XDAPS and Simple Nodal models can be applied to realistically evaluate the performance of window-shading systems.

The use of the Daylight Coefficient approach (and XDAPS formulation), applied to the estimation of irradiation passing through the window-shading device system, allows a more precise evaluation of the effect of external solar protection, and its consequences upon energy consumption. The impact of the associated lighting control strategies on the overall energy consumption can also be evaluated.

Daylight admittance and internal thermal regulation, coupled with appropriate control strategies, can reduce significantly overall energy consumption, without compromising users' preferences and comfort.

The use of new daylight illuminance metrics such as Useful Daylighting Illuminances, based on realistic time-varying sky and sun conditions, allows the quantification of internal daylight illuminance. This can be useful for the characterization of the illuminated environment and can set the basis for the estimation of electric lighting demand.

The 'Propensity to Uniformity' index, introduced in this thesis, and based on recently proposed daylighting metrics, is able to concisely describe a comprehensive range of situations occurring throughout a whole year, thus aiding the characterization of a particular scenario in daylighting terms (orientation, climate and geometry: room, window and shading device design).

The methodology proposed in this thesis for characterizing, in daylighting terms, a work space is more simple and, at the same time, more informative than previous metrics i.e., daylight factor. Both the use of UDIs for a grid of points throughout the work-plane, and the Propensity to Uniformity index, provide adequate information to analyse daylighting against the overall energy performance.

6.3 Final discussion

The complexity of the building design process and the criticality of decisions made in early stages concerning building systems were highlighted from the first chapter.

It can be argued that 'the first wave' of architectural trends towards more effective use of natural resources in buildings influenced by the Modern Movement during the 1970's, was overshadowed by the widespread use of mechanical devices and new materials leading to high levels of energy consumption. This trend continues nowadays such that a considerable quantity of energy is consumed either in the production of building materials, or in the operation of buildings themselves. This is acknowledged as responsible for almost 50% of the worldwide production of greenhouse gases (blamed as responsible for climate change) across all energy use sectors [NEF, 2005].

With the rising awareness of climate change - particularly in the 1990s - and the call for reduced energy consumption in buildings, the advantages of daylight have been re-identified. Thus the need for detailed simulation programs that integrate thermal and daylighting performance has become stronger [Selkowitz, 1998]

As shown in the literature review, simulation techniques have been assisting conscientious building design. The research in this thesis refers in particular to the precise simulation of window-shading systems. Within window-shading system analysis, two different tendencies can be distinguished. One of this tendencies uses simulation to consider the influences of geometry in design and its consequences in energy use in buildings. The other is the simulation of the behaviour of specialised products such as: new glazing materials, advanced framing systems and dynamic electronic controls applied to shadings or lighting systems.

Geometry's influence in design does not seem able to fullfill all the requirements that the latest regulations and efficiency strategies promote (European Directive, LEED, etc.)[22]. Therefore new technologies have come onto the scene exploiting advanced building envelope systems which can out-perform traditional ones.

As an example of what was said in the preceding paragraph, recent studies in the field of window-shading system performance, analysed prototype windows (electrochromic, EC), reporting that they can provide maximum heating load reduction for high 'window to wall ratios' [Papaefthimiou, 2006]. In combination with overhangs, the performance of such highly industrialised material reported 'modest' energy savings since opaque protection can avoid direct sun which EC windows are unable to do alone [Lee et al., 2007].

This suggests that the previously mentioned tendencies to do either a geometry or a 'specialized materials' centred simulations, should definitely addressed together in order to tackle such a complex challenge: a geometry which can ensure the exploitation of natural resources i.e., natural light and ventilation available in each locale while also using advanced materials for which the embodied energy does not affect overall CO_2 emissions significantly.

Economic development and energy consumption have been always considered proportionally linked (i.e., the level of industrialization of a region or country is often measured in terms of energy consumption). The prevalent belief in some industrialized regions, that a reduction in greenhouse gas emissions can be solved merely through the use of more

22. For example the use of light-shelves, in some latitudes and orientations, saves energy due to electric lighting but cannot cater for visual and thermal comfort. At a glace see Figure B-1, "Energy Consumption for Adelaide, Australia.," on page 183.

applied technology is, in the light of this research work, judged at least as insufficient.

The hybrid dynamic lighting thermal model presented in this thesis, as well as proving the ability of geometry and basic materials to reduce energy consumption, is also able to process more complex materials. A rational integration of the benefits of technology advances with solar geometry knowledge applied to building envelope design, seems to be the most sensible path to follow.

6.4 Recommendations for future work

Potential future work can possibly include an integrated study of the influence of shading devices in ventilation as the ventilation component has a significant impact in energy savings for cooling in many climates. This would take the research of this thesis a step forward towards an even more holistic building prediction system.

This study proposed an index for the characterization of daylight quality for non-domestic rooms (multi-occupant offices and classrooms). However, in order to gain a more descriptive approach it would be possible to establish a scale for this index based on studies of occupants' preferences.

This thesis assumed a range of useful illuminances between 100 and 2000 lux across the whole 'working year'. Future research could analyse if there should be different ranges of values, depending on specific building functions and visual tasks (i.e., other non-domestic buildings such as warehouses or factories).

There is the possibility to explode the capabilities of this methodolgy for exploring the effect of different envelope systems combined with dynamic facade systems (i.e. electrochromic glazing or automated blinds) and their integration with daylight linked electric lighting systems. Another possibility is to explore more in depth the thermal effects of varied glazing types and various combinations of fabric types togehter with different scheme of internal gains depending on buildings' functions (different types of non-domestic buildings). This can improve comfort conditions (visual and thermal) and effectively reduce the overall energy demand.

Future studies could investigate in more depth how embodied energy can affect CO_2 emissions when considering all components i.e., shading devices, window frame, advanced glazing systems, interior shading, etc.

A possible field of research could be using the same approach for modelling the influence of the urban conformation, when represents shading or diffuse irradiation from external elements, in both the quality of the illuminated environment and the thermal comfort (i.e., shading and reflections from surrounding buildings or street trees, etc.).

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Appendix

A Daylight Performance Results: U.D.I.

A.1 Useful Daylight Illuminances

A.1.1 Point by point UDIs for Adelaide, Australia

South: Attention should be drawn on locales in the South Hemisphere where the first orientation analysed is always South, this is the orientation which receives the less irradiation in this hemisphere (similar to North in the Northern hemisphere).

For this climate in south orientation, the quality of the illuminated environment can be high with most of the shading alternatives (excluding the unshaded option). The PU index is always over 0.5 here, reaching 0.85 for the H0 shading option. In terms of energy consumption the same appreciation is valid as all the options perform closely. Therefore, from external light-shelves to horizontal or vertical louvres can provide both good uniformity throughout the working year and a relatively similar level of energy consumption.

West and East: variations can be appreciated for these two orientation showing H45 and Vp45 performing the best for lighting evaluation with values of PU index around 0.80, whereas for energy consumption H0 shows the lowest consumption for the ON/OFF switching scheme and H45 does it for the TOP/UP one.

North: being the southern hemisphere, this orientation receives the highest irradiation. A significant difference can be perceived between the H45 case and the rest as this shows a PU index of 0.76, others cannot exceed 0.31 (with an Unshaded case in 0.08). The UDI Exceeded shows clearly very high values near the window which are hard to 'smooth'. Going to the energy consumption evaluation confirms that the H45 has the lowest consumption with the TOP/UP scheme (being the H0 the option with lowest consumption for the ON/OFF scheme).

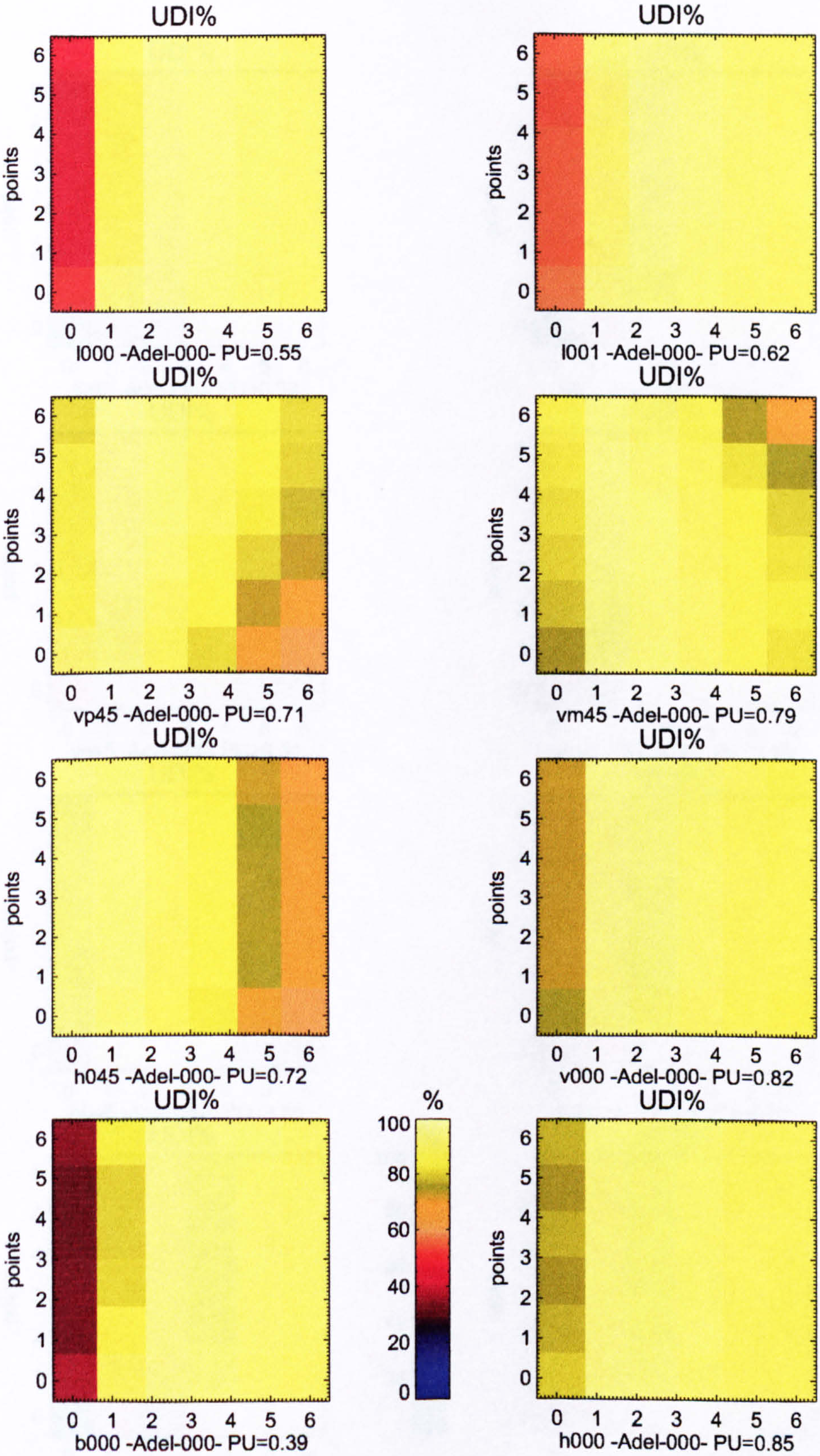

Figure A-1 UDIs point by point for Adelaide, Australia (South)

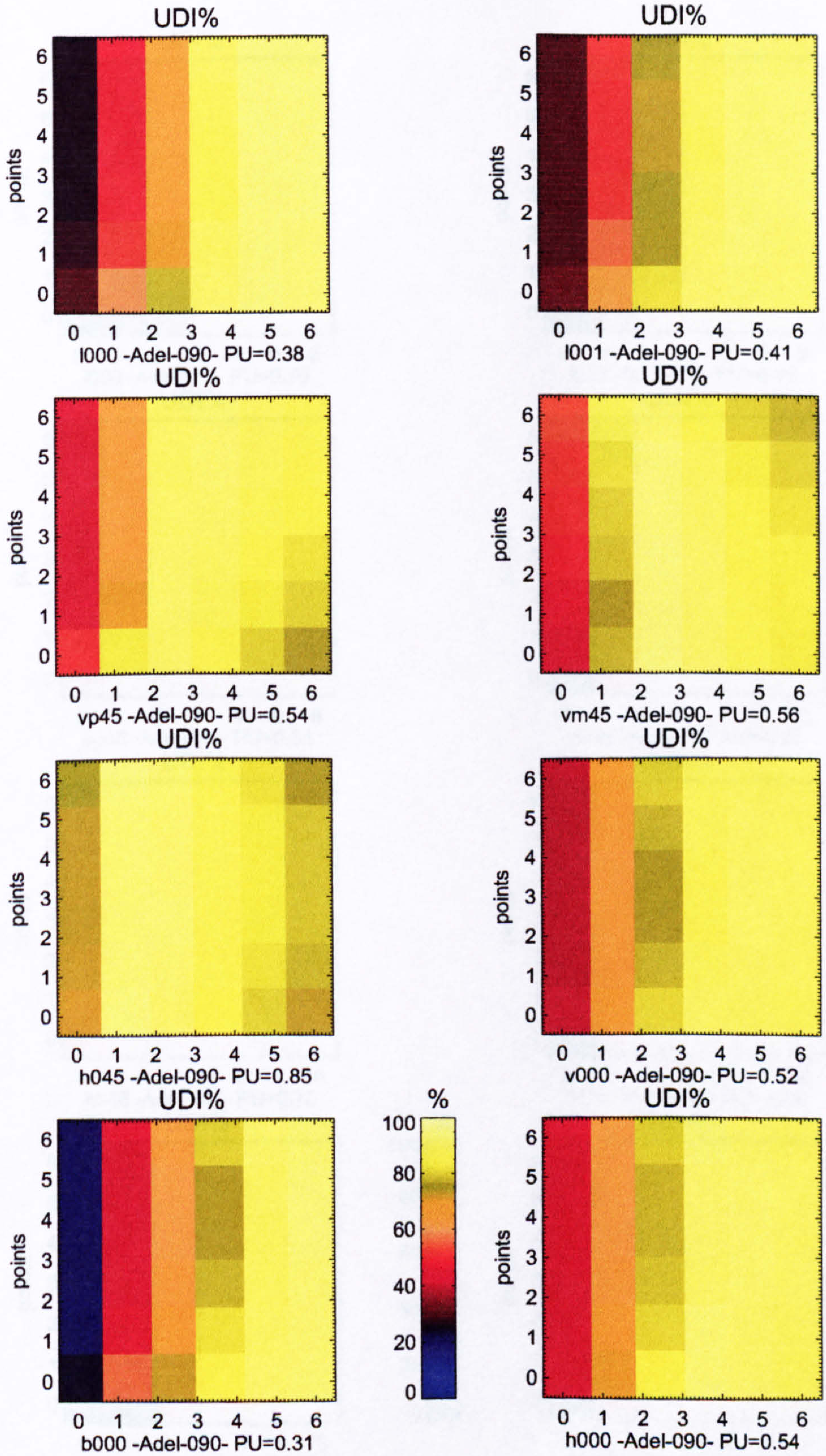

Figure A-2 UDIs point by point for Adelaide, Australia (West)

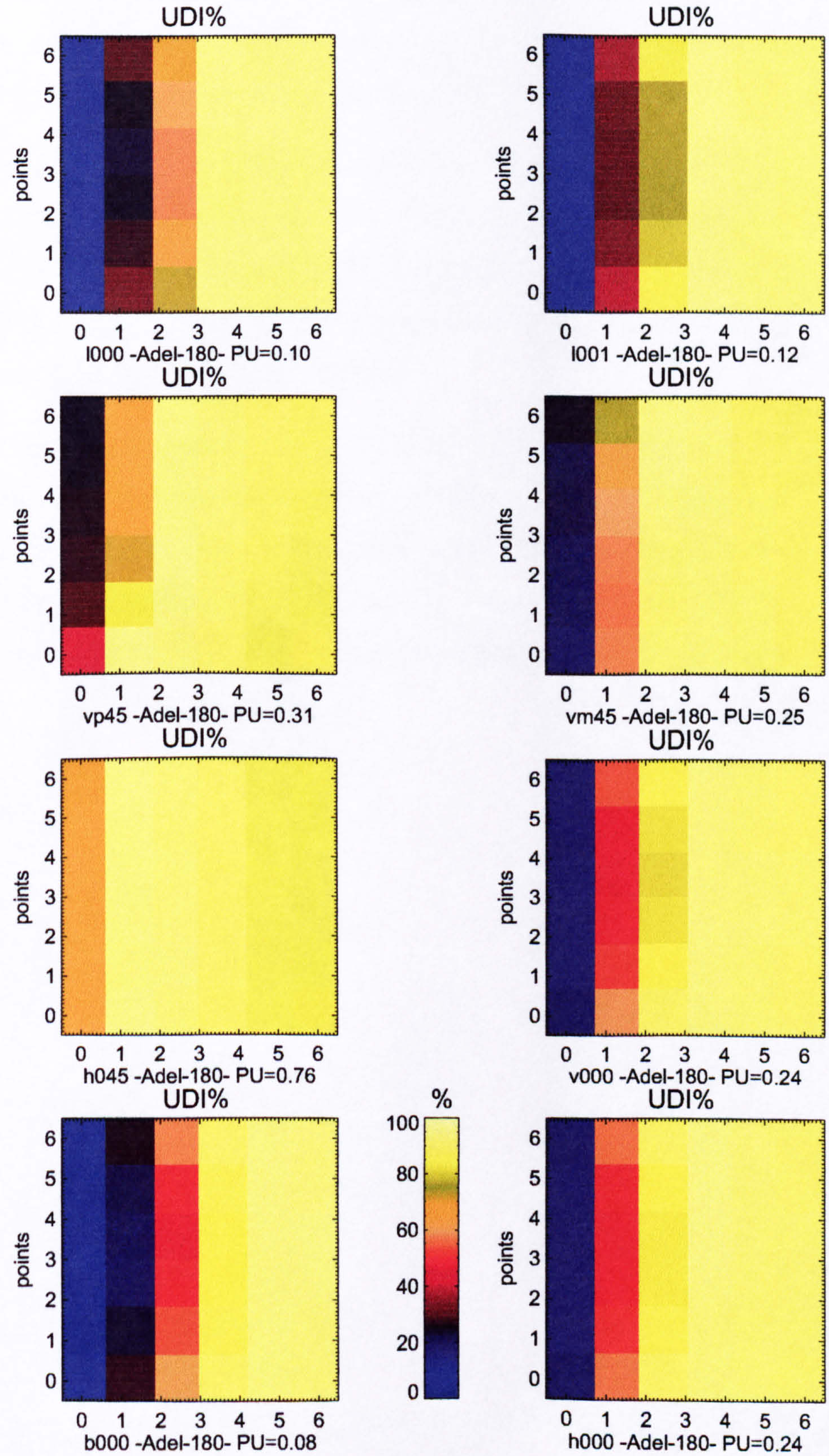

Figure A-3 UDIs point by point for Adelaide, Australia (North)

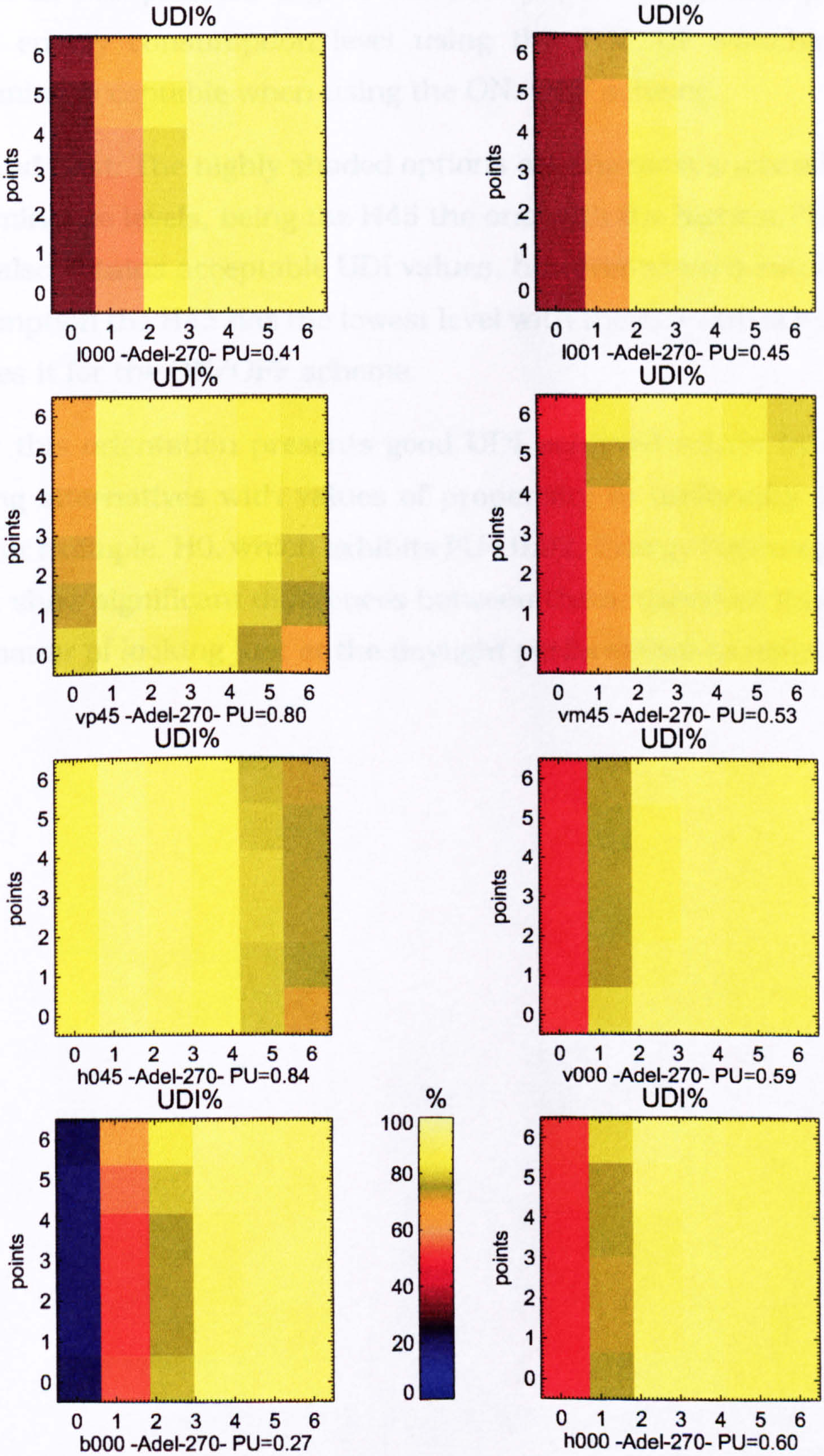

Figure A-4 UDIs point by point for Adelaide, Australia (East)

A.1.2 Point by point UDIs for Algiers, Algeria

South: a noticeable difference of H45 with respect to the rest of the shading options as this presents a good uniformity (PU= 0.82), also presents the lowest energy consumption level using the TOP/UP switching scheme, performing acceptable when using the ON/OFF scheme.

West and East: The highly shaded options are the most successful in terms of illuminance levels, being the H45 the one with the highest PU value. The Vp45 also obtains acceptable UDI values, however when it comes to energy consumption the H45 has the lowest level with the TOP/UP scheme and the H0 does it for the ON/OFF scheme.

North: this orientation presents good UDI achieved values in most of the shading alternatives with values of propensity to uniformity significantly high, for example, H0, which exhibits PU= 0.92. Energy consumption values do not show significant differences between them, therefore this case could be a matter of looking just at the daylight performance to make a decision.

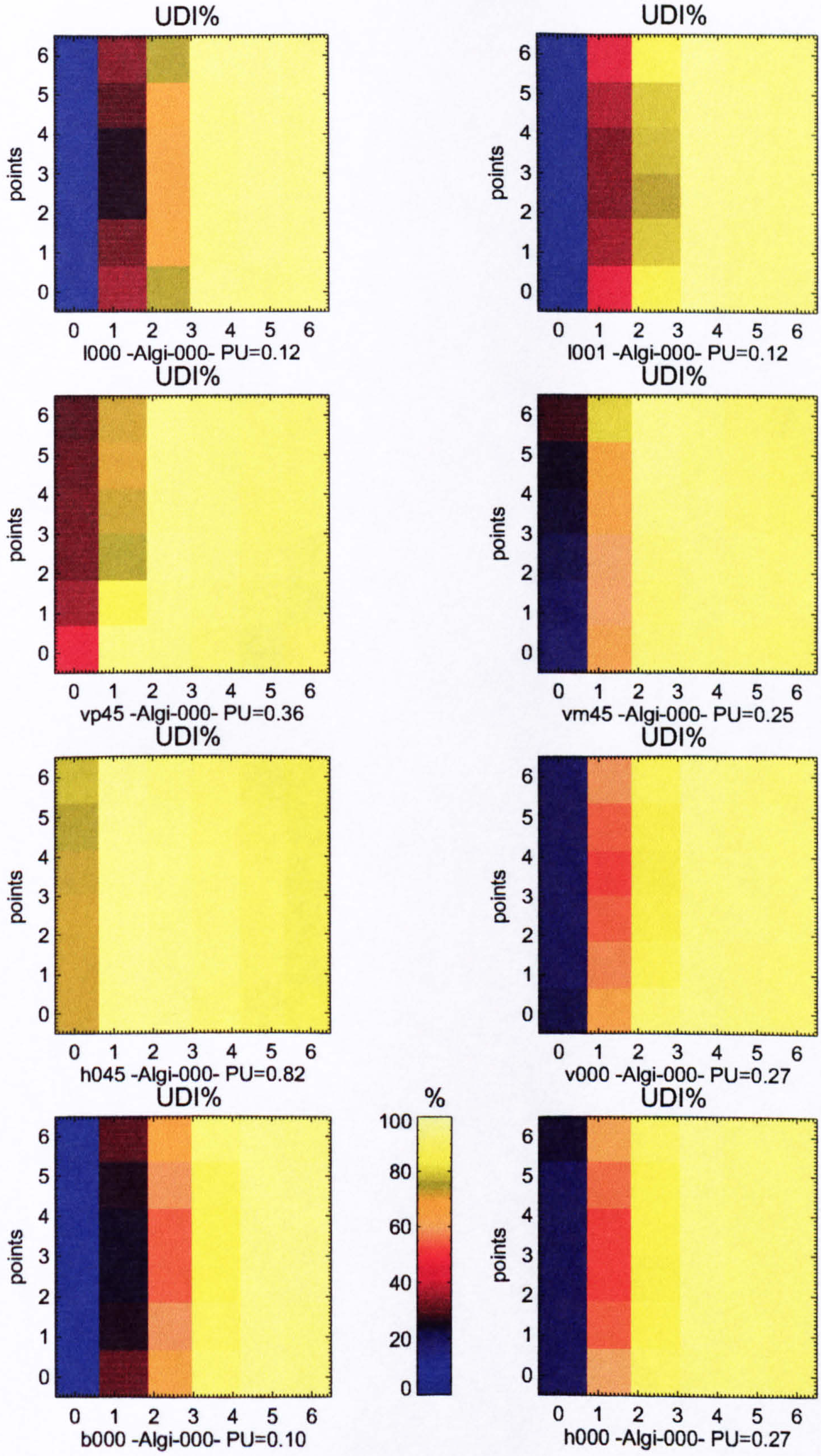

Figure A-5 UDIs point by point for Algiers, Algeria (South)

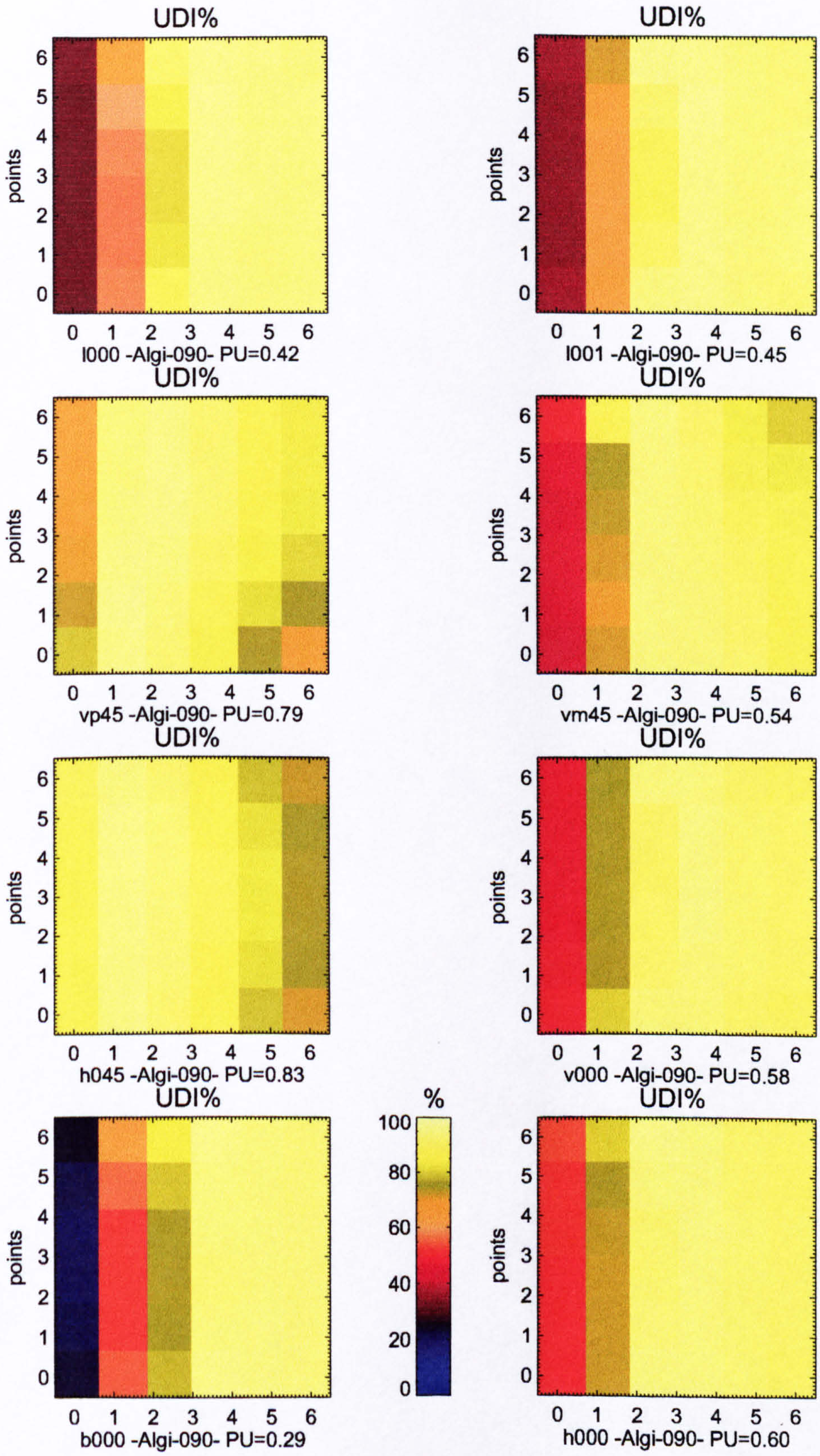

Figure A-6 UDIs point by point for Algiers, Algeria (West)

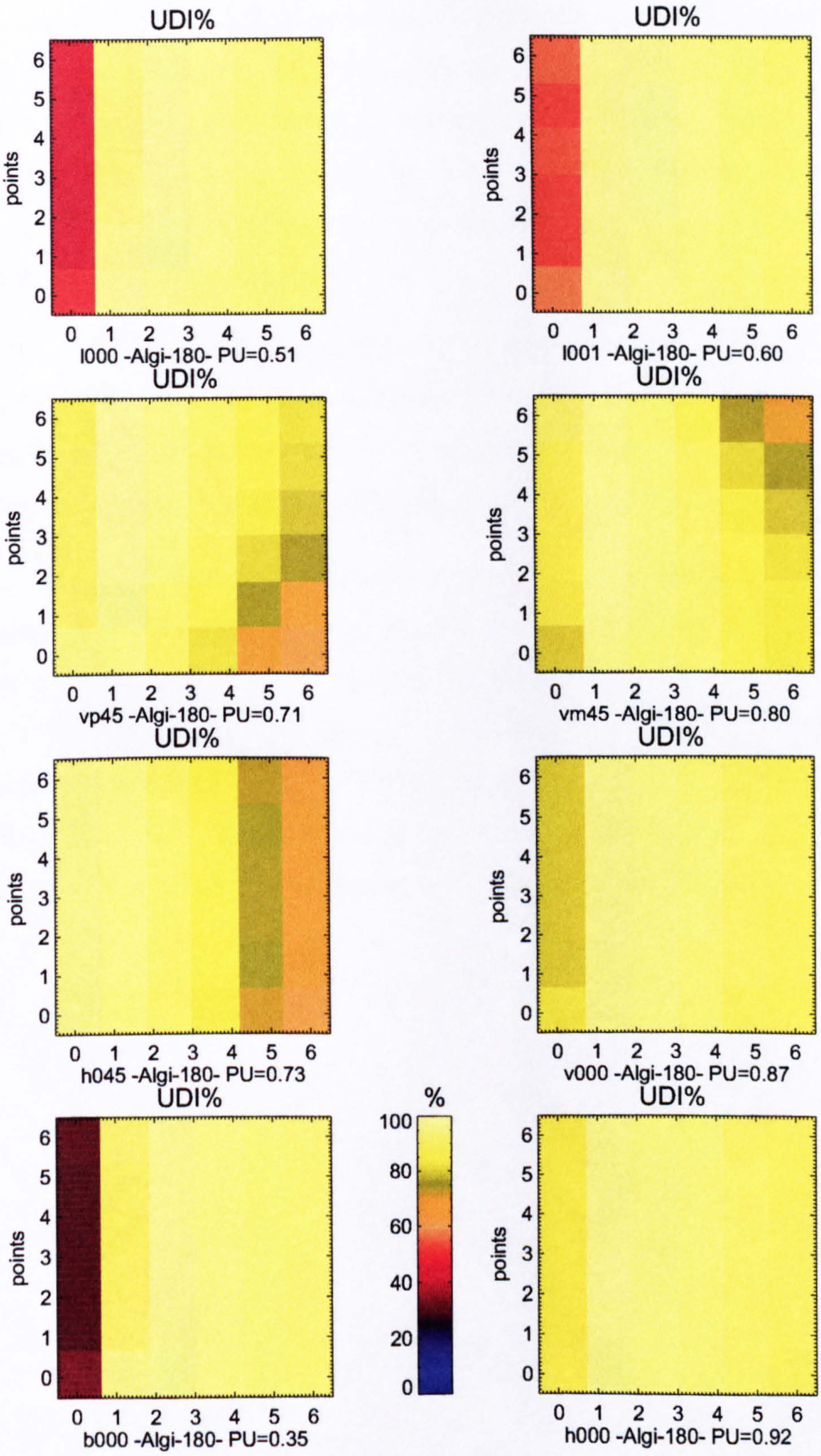

Figure A-7 UDIs point by point for Algiers, Algeria (North)

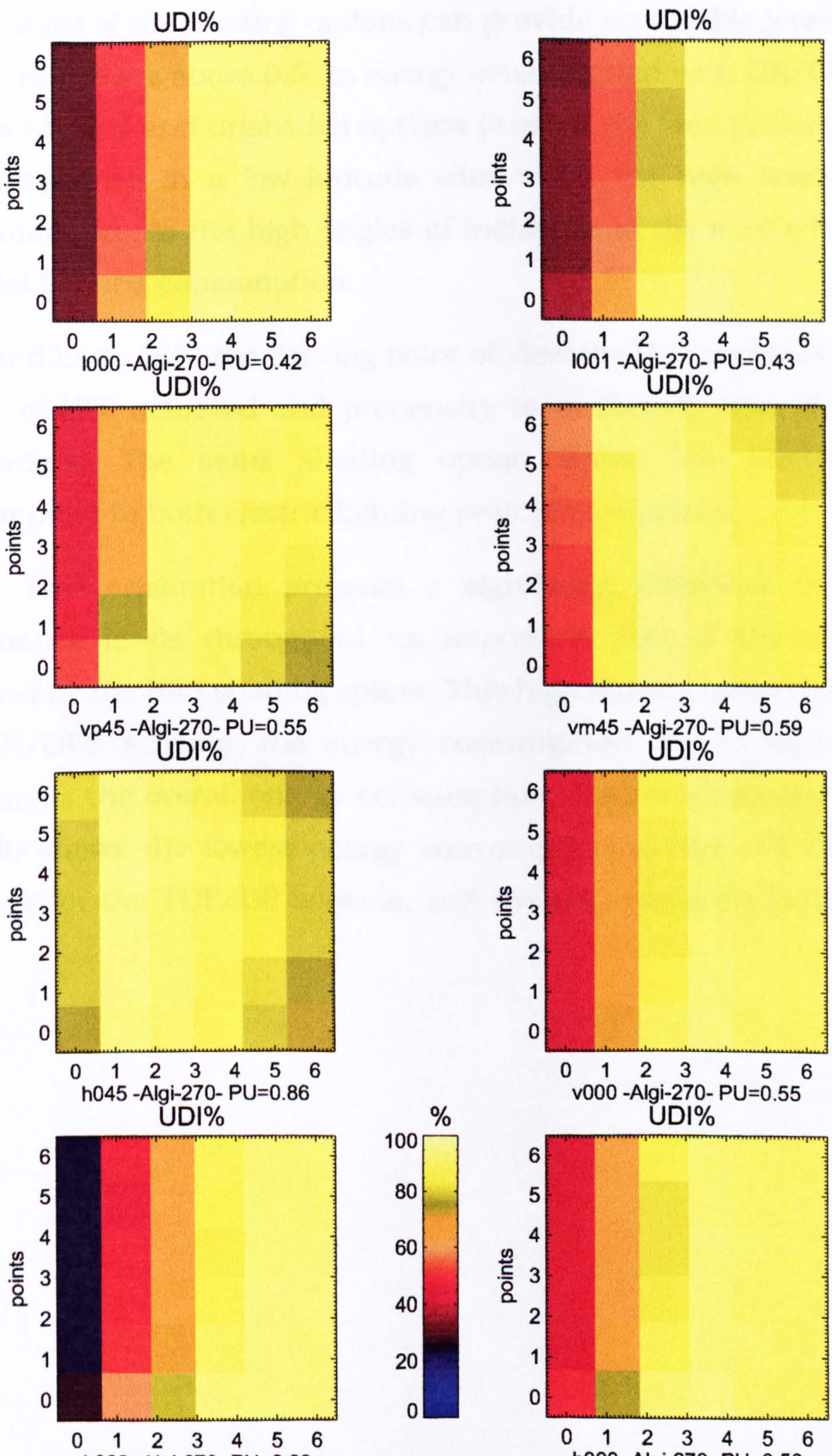

Figure A-8 UDIs point by point for Algiers, Algeria (East)

A.1.3 Point by point UDIs for Arequipa, Peru

South: most of the shading options can provide acceptable levels of UDI, all the PU values are above 0.5. In energy consumption with ON/OFF scheme, the low shaded and unshaded options present the best performance. This being explained in a low latitude climate by the high levels of diffuse irradiation (due to the high angles of incidence of the sun) which reduces artificial lighting consumption.

West and East: from the lighting point of view the H45 provides the highest values of UDI achieved and propensity to uniformity over 0.75 for both orientations. The same shading option shows low levels of energy consumption in both electric lighting switching schemes.

North: This orientation presents a significant difference in the useful illuminance levels throughout an important part of the working year obtained by the H45 shading option. This high shaded option makes that in the ON/OFF scheme, the energy consumption due to electric lighting increments the overall energy consumption. A medium shaded alternative like H0 shows the lowest energy consumption for the ON/OFF scheme. However for the TOP/UP scheme, still the H45 performs better than any other.

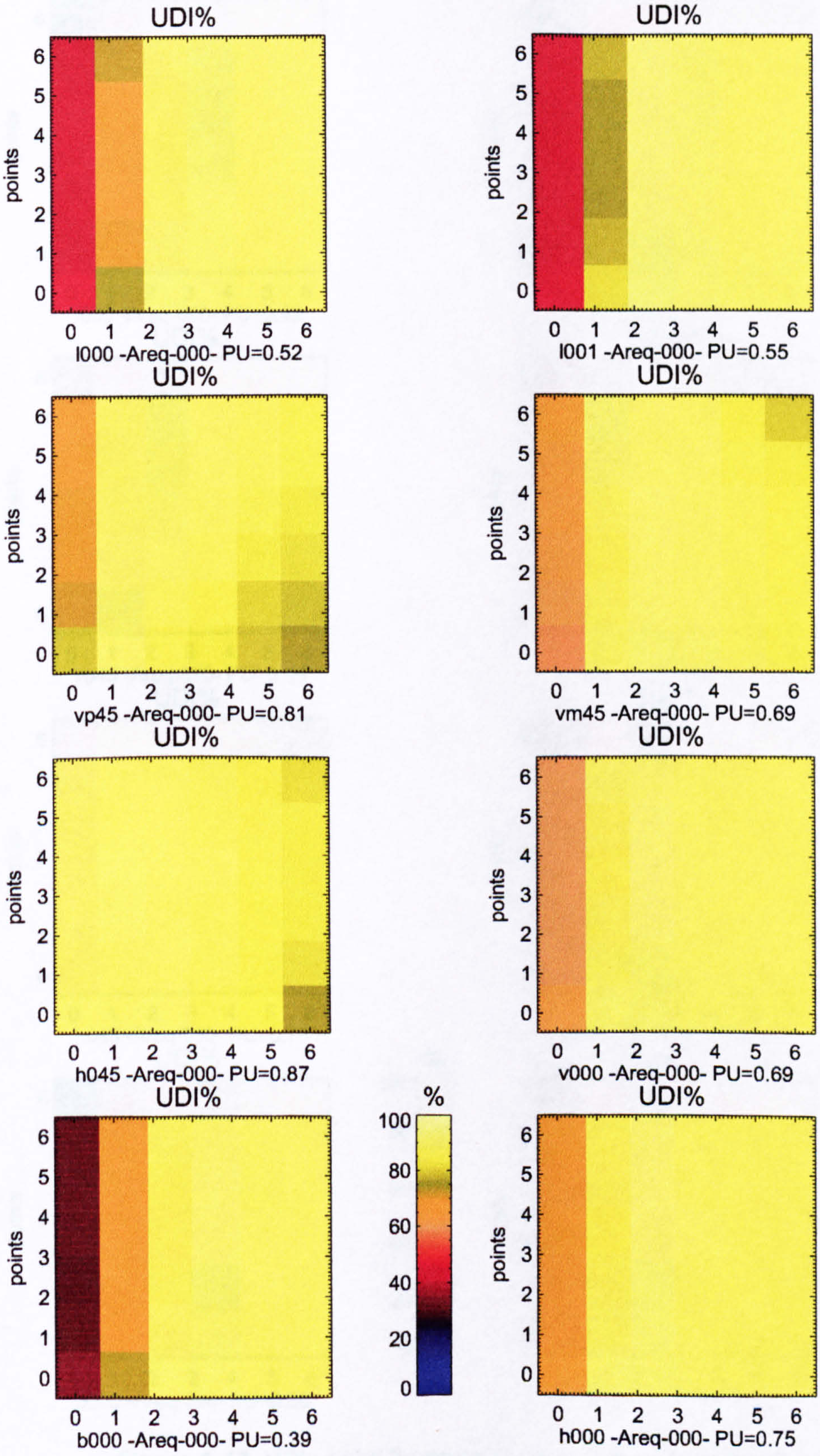

Figure A-9 UDIs point by point for Arequipa, Peru (South)

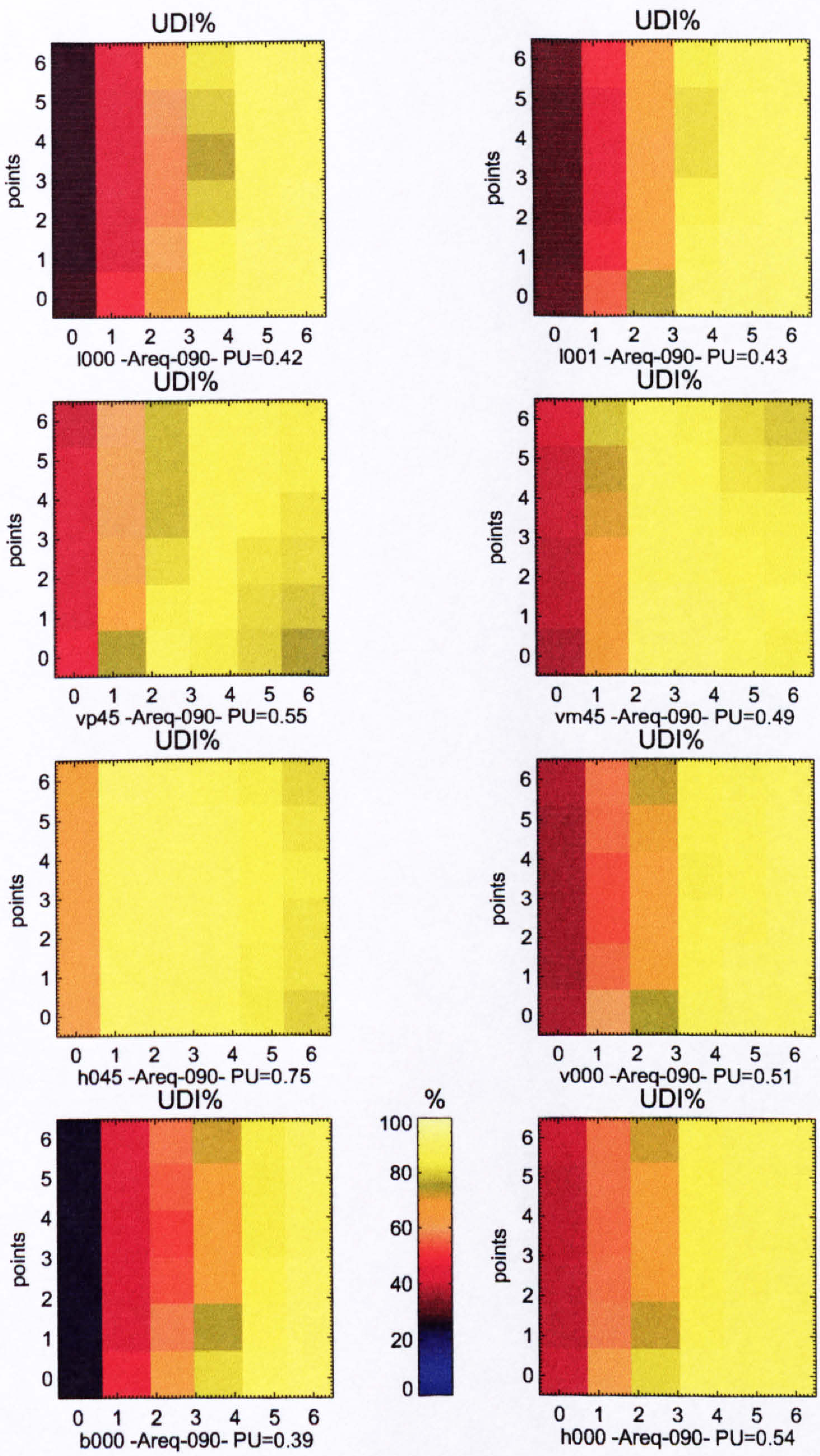

Figure A-10 UDIs point by point for Arequipa, Peru (West)

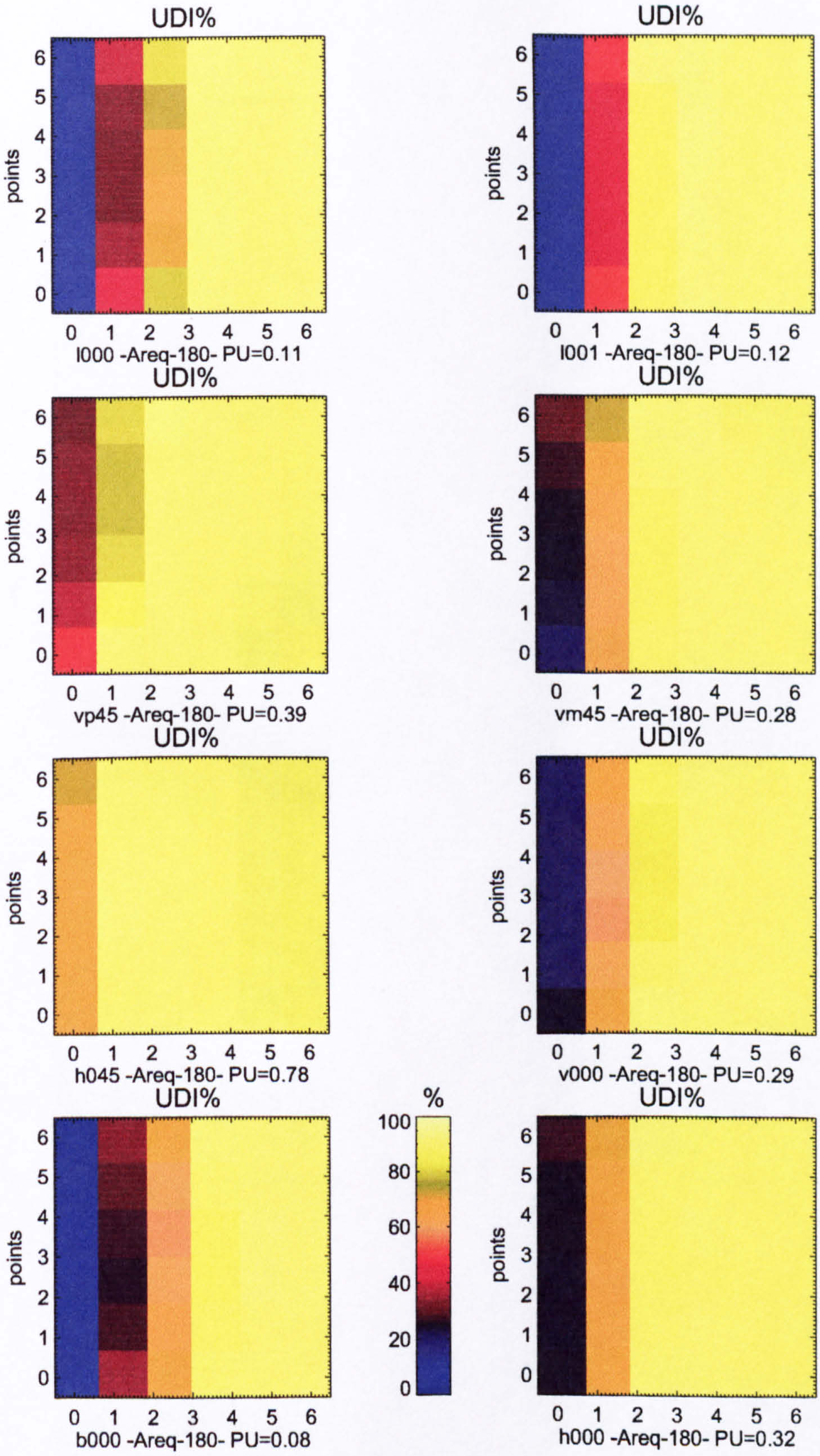

Figure A-11 UDIs point by point for Arequipa, Peru (North)

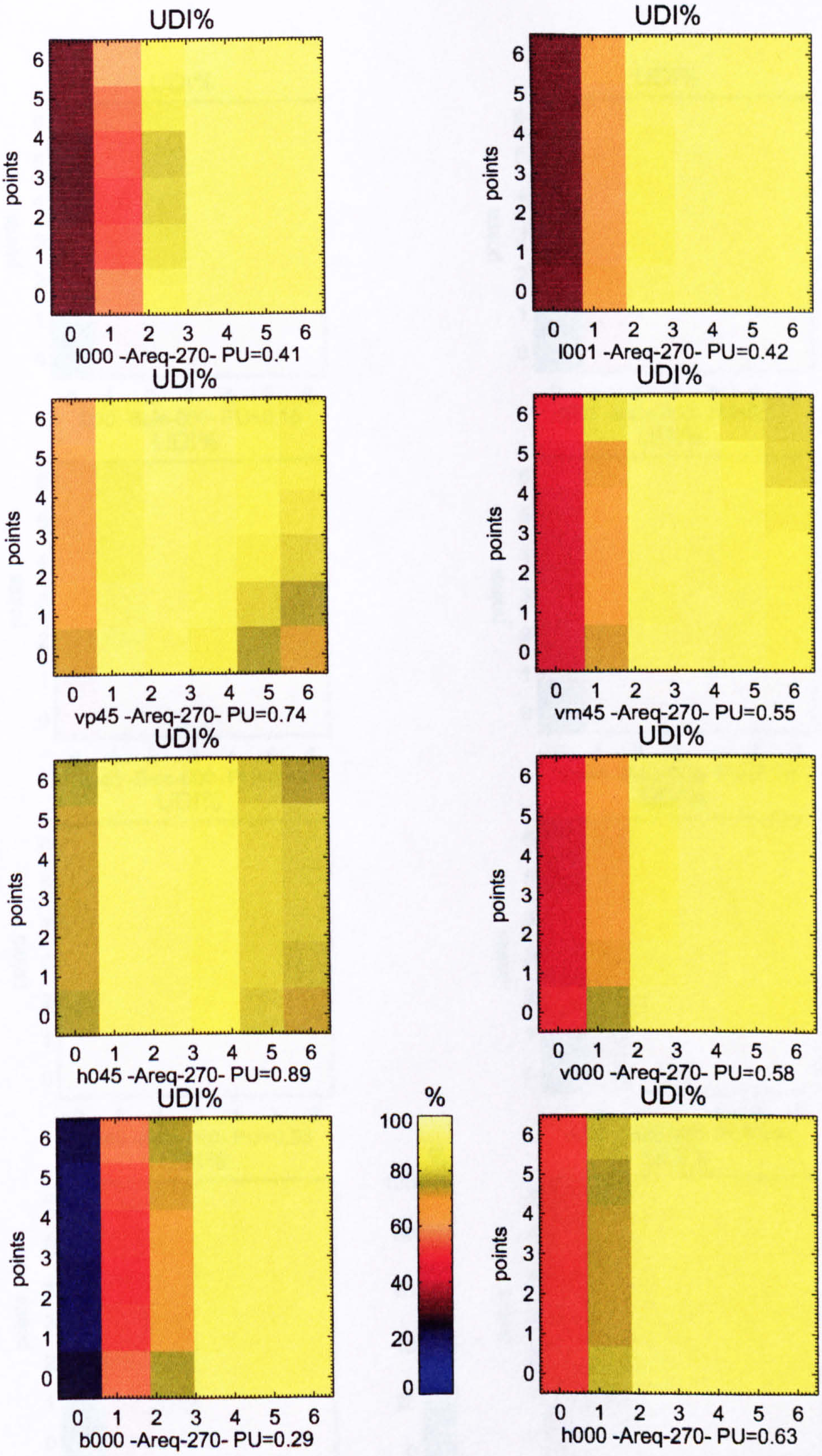

Figure A-12 UDIs point by point for Arequipa, Peru (East)

A.1.4 Point by point UDIs for Belem, Brazil

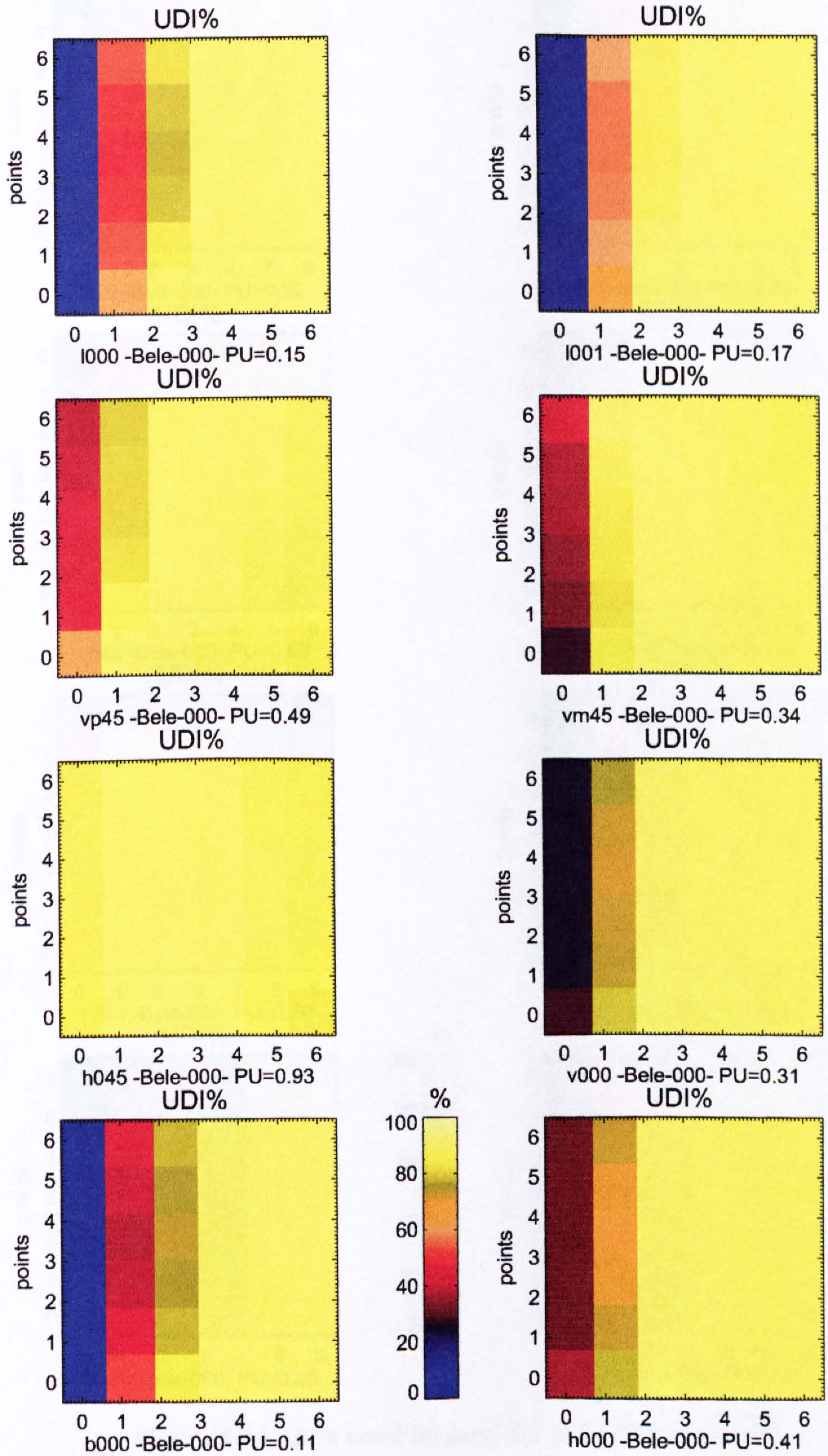

Figure A-13 UDIs point by point for Belem, Brazil (South)

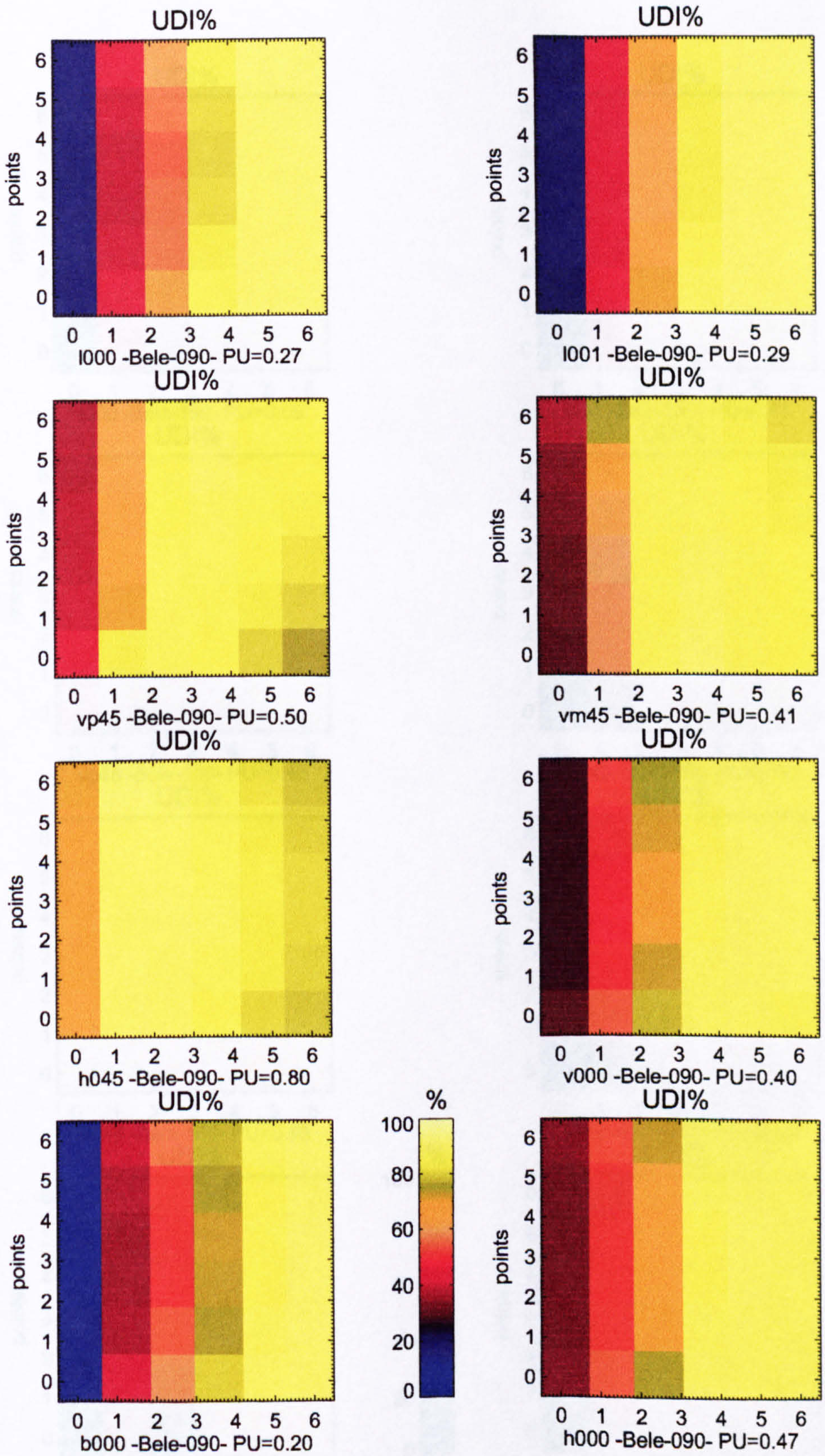

Figure A-14 UDIs point by point for Belem, Brazil (West)

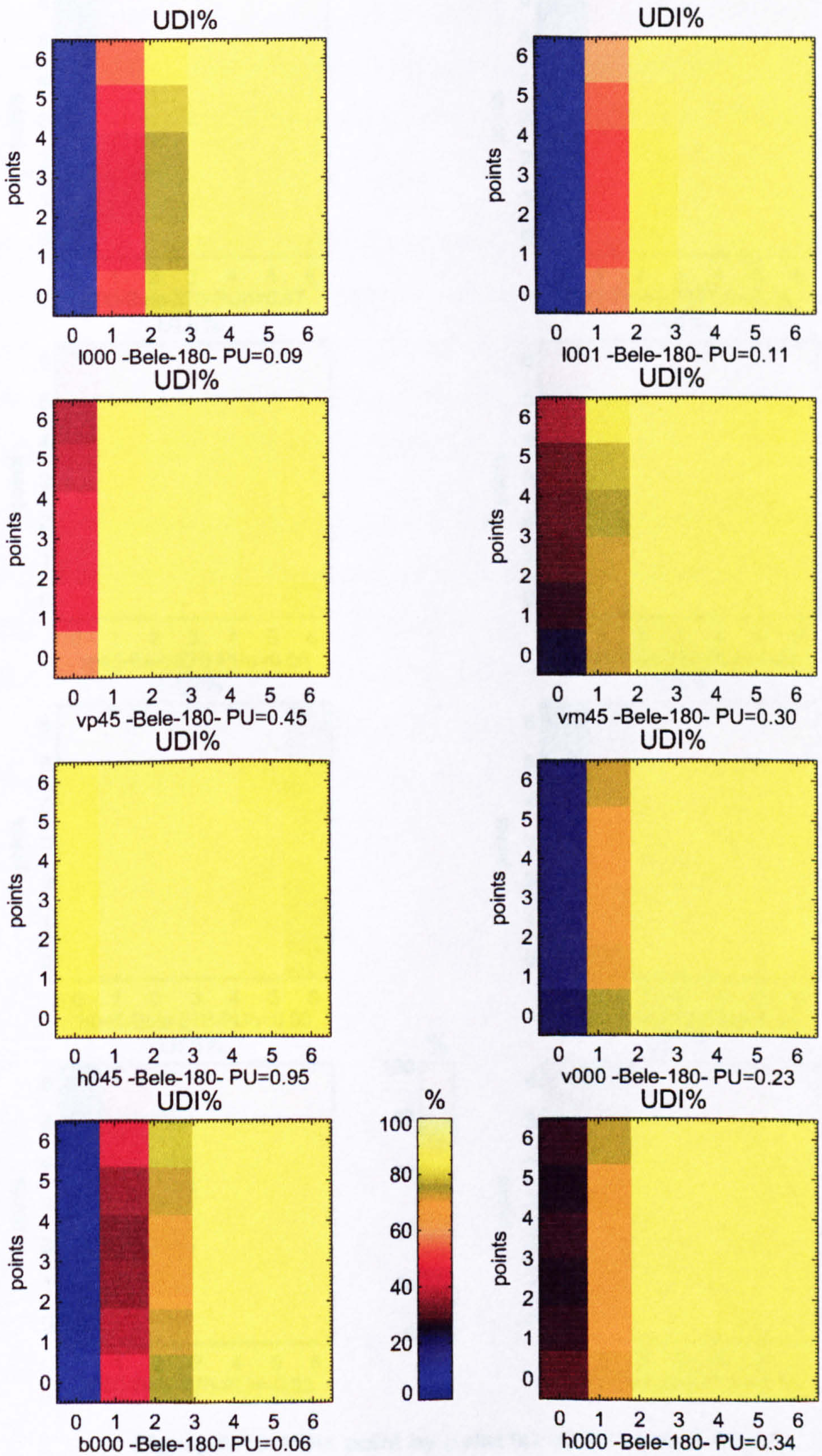

Figure A-15 UDIs point by point for Belem, Brazil (North)

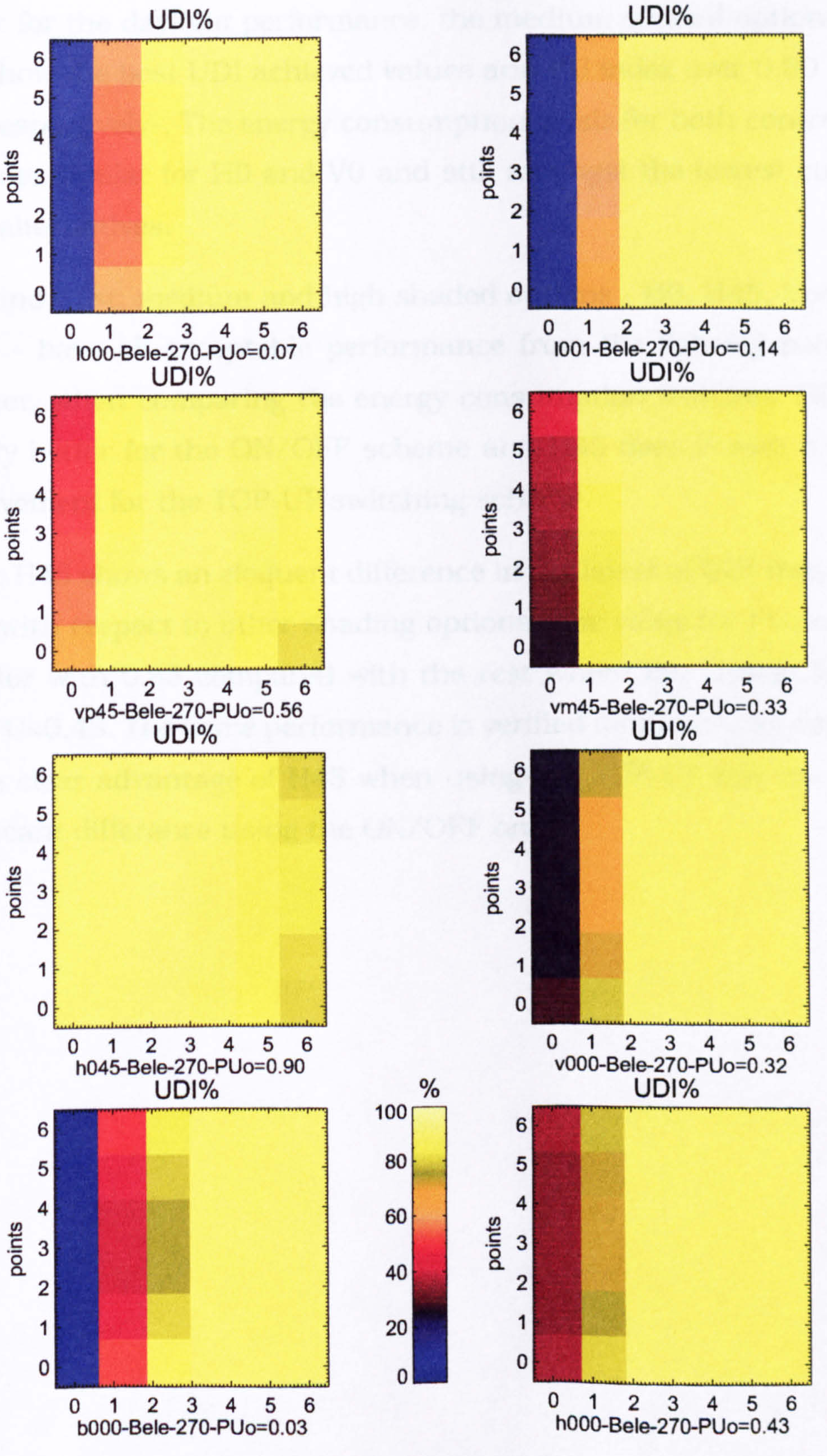

Figure A-16 UDIs point by point for Belem, Brazil (East)

A.1.5 Point by point UDIs for Buenos Aires, Argentina

South: for the daylight performance, the medium shaded options - H0 and V0 - show the best UDI achieved values and PU index over 0.80 - 0.88 and 0.84 respectively-. The energy consumption levels for both control schemes are quite similar for H0 and V0 and still amongst the lowest compared to other alternatives.

West and East: medium and high shaded options - H0, H45, Vp45, V0 and Vm45 - have all acceptable performance from the lighting point of view, however, when comparing the energy consumption features, H0 performs slightly better for the ON/OFF scheme and H45 does it with a significant improvement for the TOP-UP switching scheme.

North: H45 shows an eloquent difference in the levels of UDI throughout the room with respect to other shading options. The value for PU index is also superior with 0.83 compared with the rest where the closest is the Vp45 with PU=0.43. The same performance is verified for the energy consumption with a clear advantage of H45 when using the TOP-UP scheme and a less significant difference using the ON/OFF one.

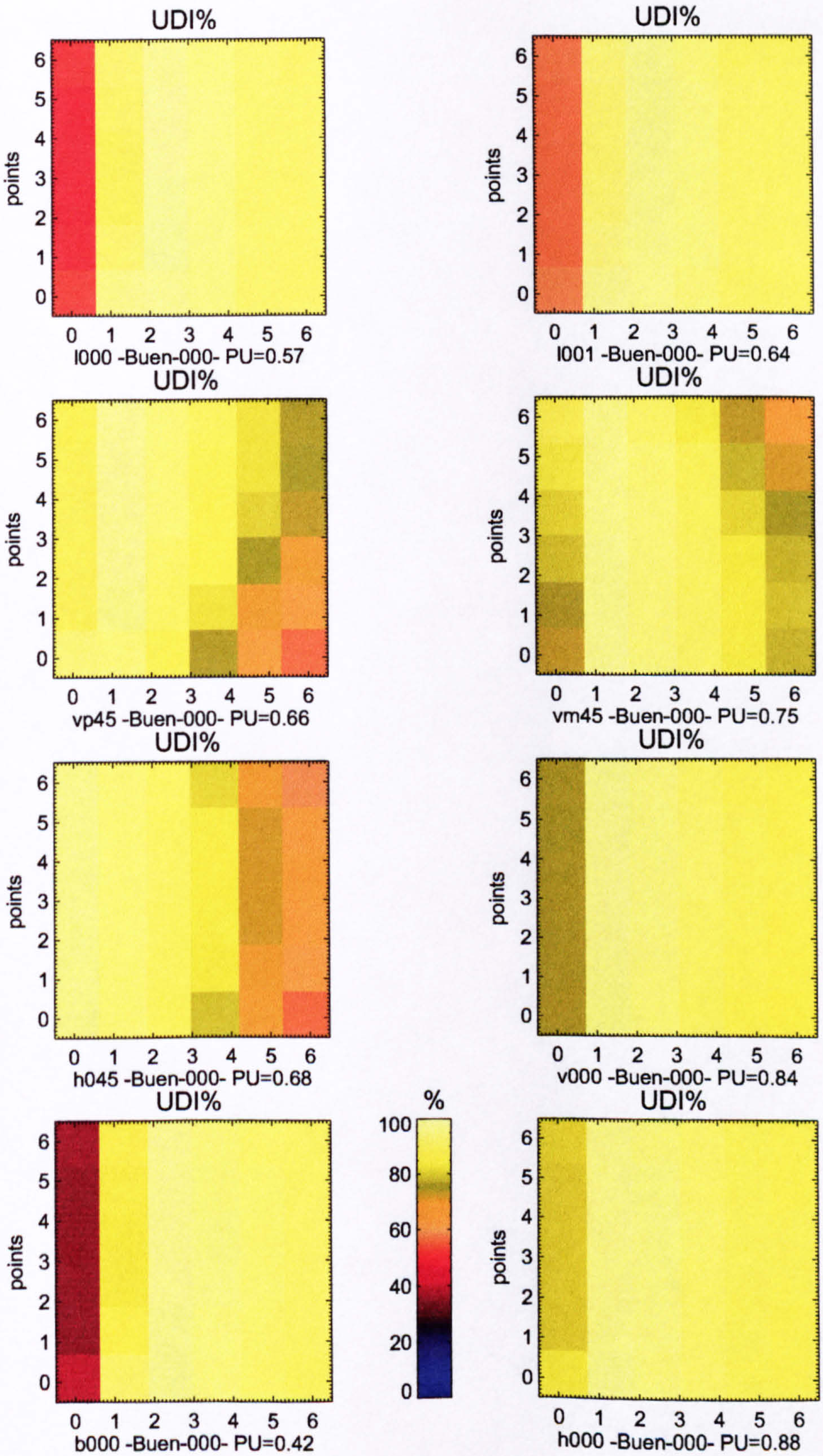

Figure A-17 UDIs point by point for Buenos Aires, Argentina (South)

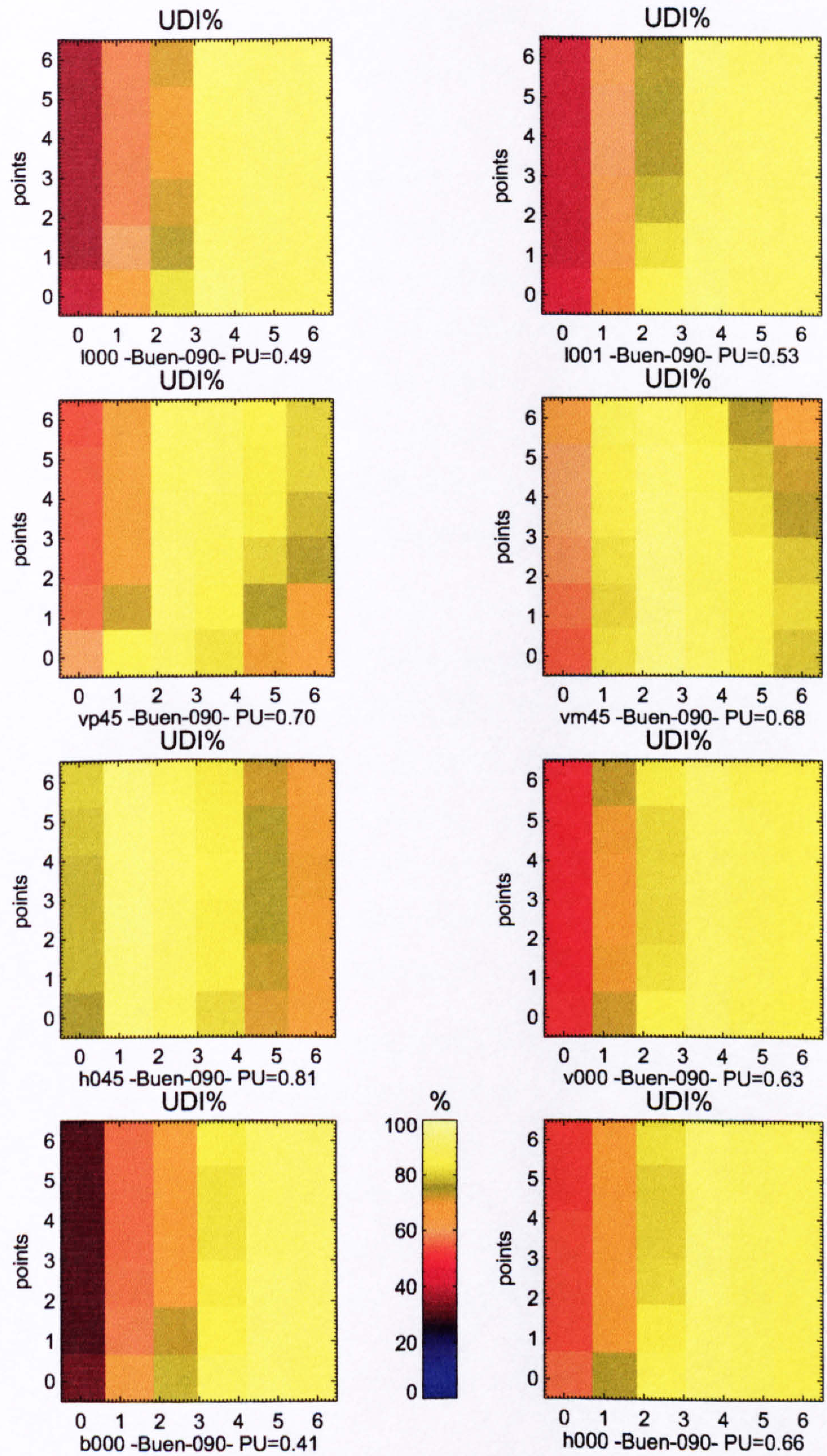

Figure A-18 UDIs point by point for Buenos Aires, Argentina (West)

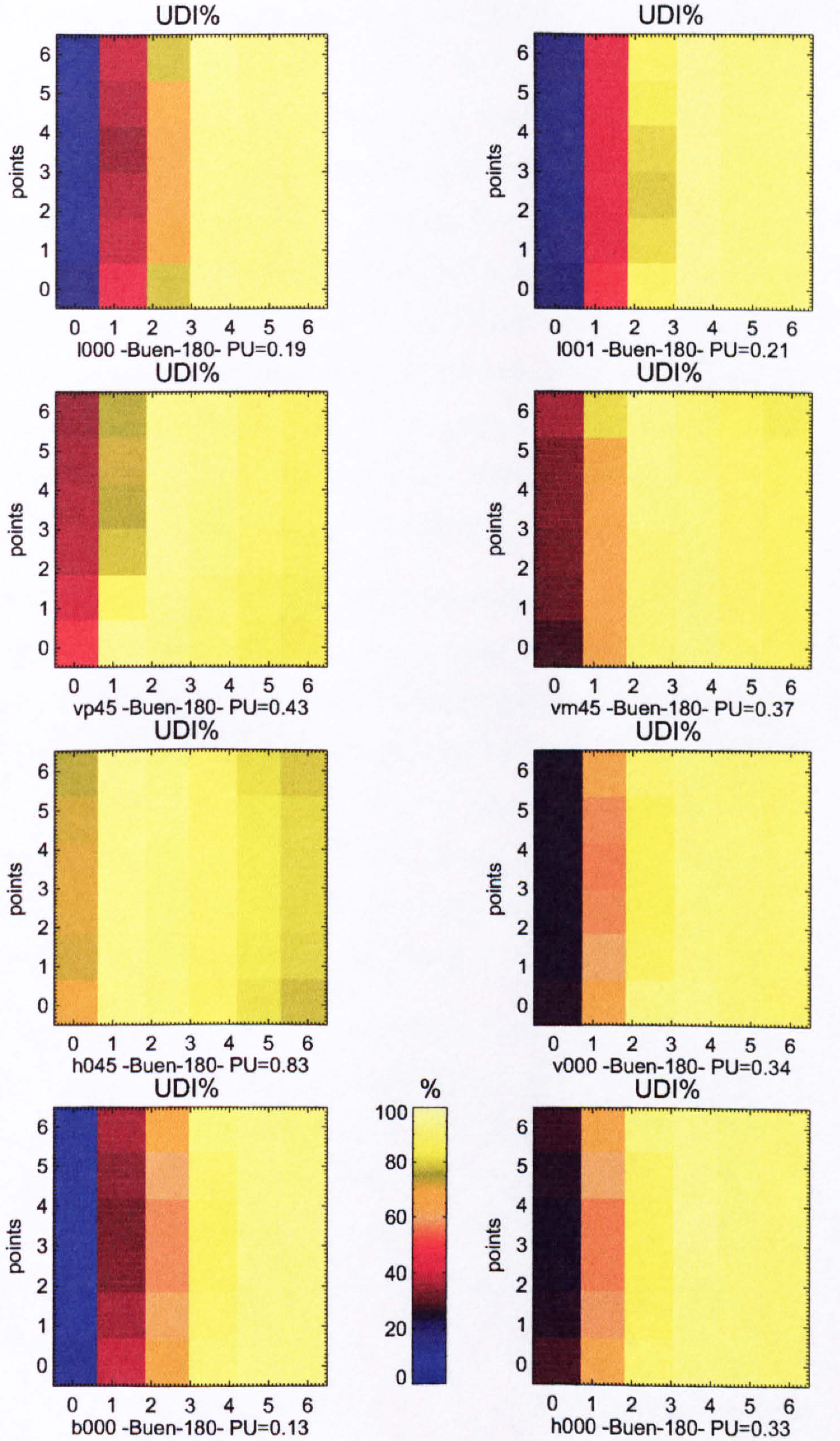

Figure A-19 UDIs point by point for Buenos Aires, Argentina (North)

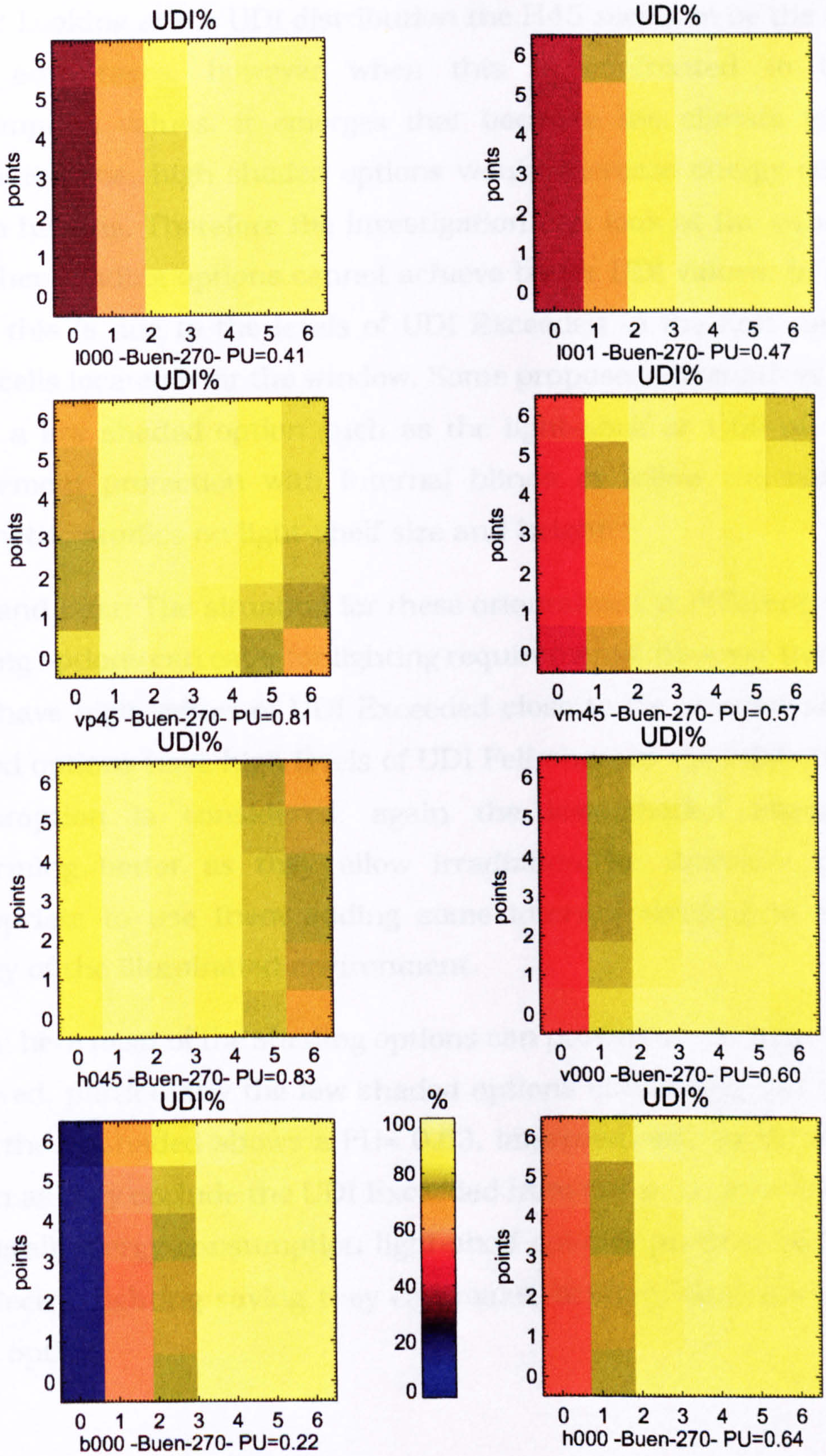

Figure A-20 UDIs point by point for Buenos Aires, Argentina (East)

A.1.6 Point by point UDIs for Fairbanks, Alaska, U.S.

South: Looking at the UDI distribution the H45 seems to be the option with more advantages, however when this is confronted to the energy consumption values, it emerges that because the climate is a heating dominated one, high shaded options would increase energy consumption due to heating. Therefore the investigation can look at the causes on why the other shading options cannot achieve better UDI values. In most of the cases this is due to the levels of UDI Exceeded in the first row of virtual photocells located near the window. Some proposed alternatives could be to adopt a low shaded option such as the light-shelf at 1.60 m. height and supplement protection with internal blinds or follow the research with parametric studies on light-shelf size and height.

West and East: The situation for these orientations is different, most of the shading options can cater for lighting requirements, however the low shaded ones have high values of UDI Exceeded close to the window and the high shaded options have high levels of UDI Fell-short at the back. If the energy consumption is considered, again the low shaded alternatives are performing better as they allow irradiation in; therefore it might be appropriate to use them adding some internal shading to improve the quality of the illuminated environment.

North: here most of the shading options can provide acceptable levels of UDI achieved, particularly the low shaded options obtain high PU index levels. Even the unshaded shows a PU= 0.63, improved only by the light-shelves option as they occlude the UDI Exceeded from the area close to the window. In overall energy consumption light-shelf options perform better based in the electric lighting saving they can make, heating loads are high for any other option.

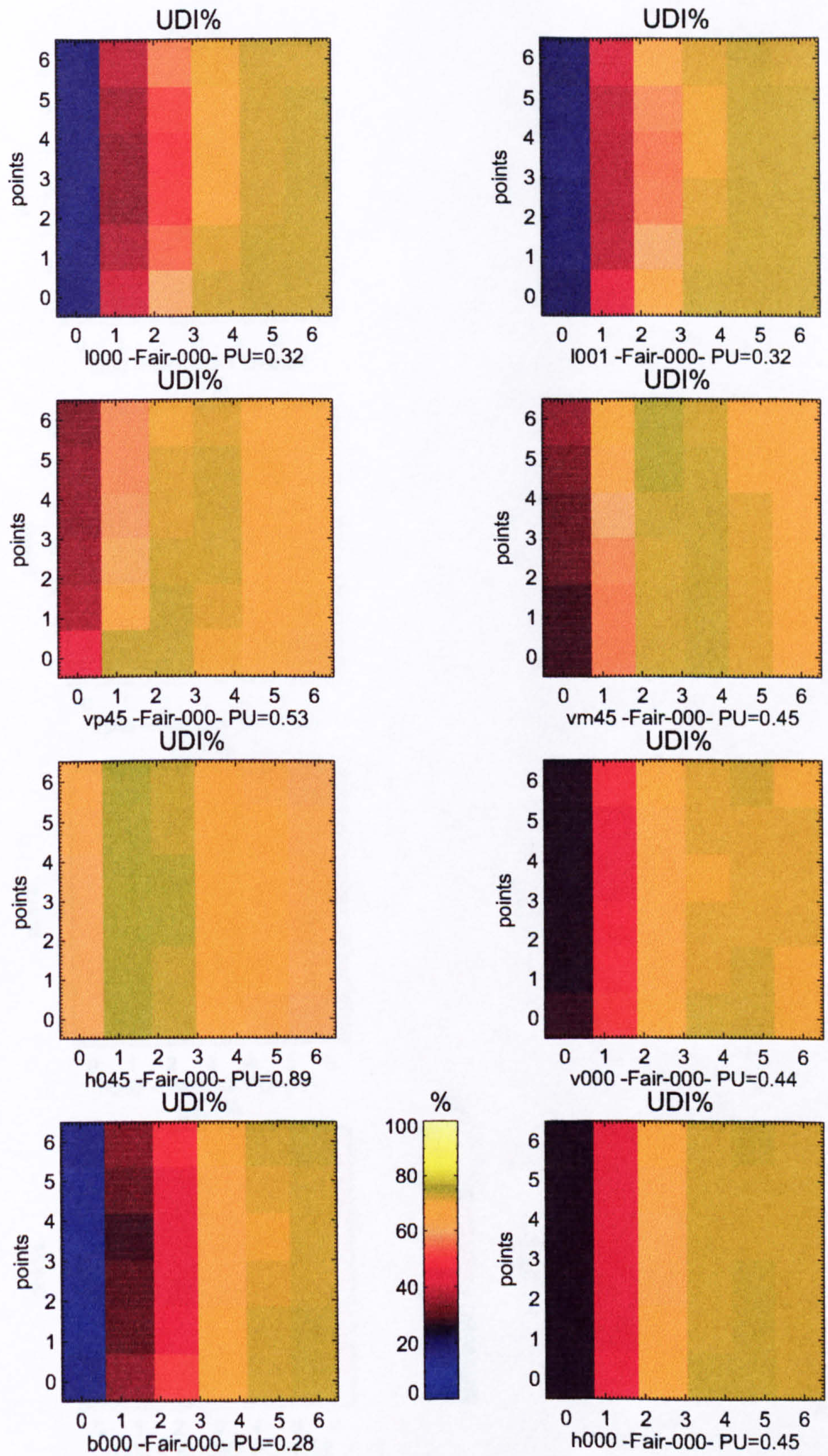

Figure A-21 UDIs point by point for Fairbanks, Alaska, U.S. (South)

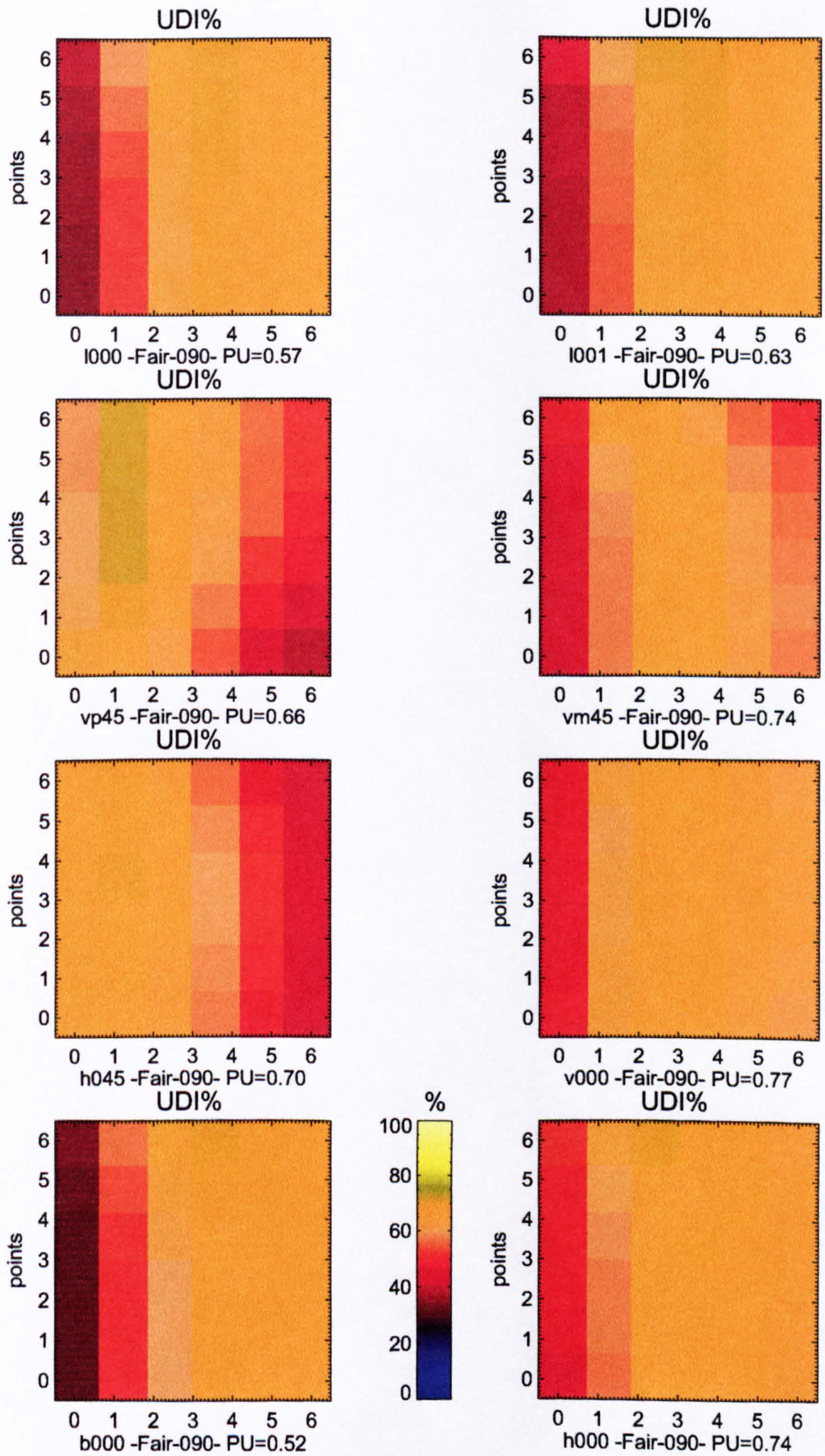

Figure A-22 UDIs point by point for Fairbanks, Alaska, U.S. (West)

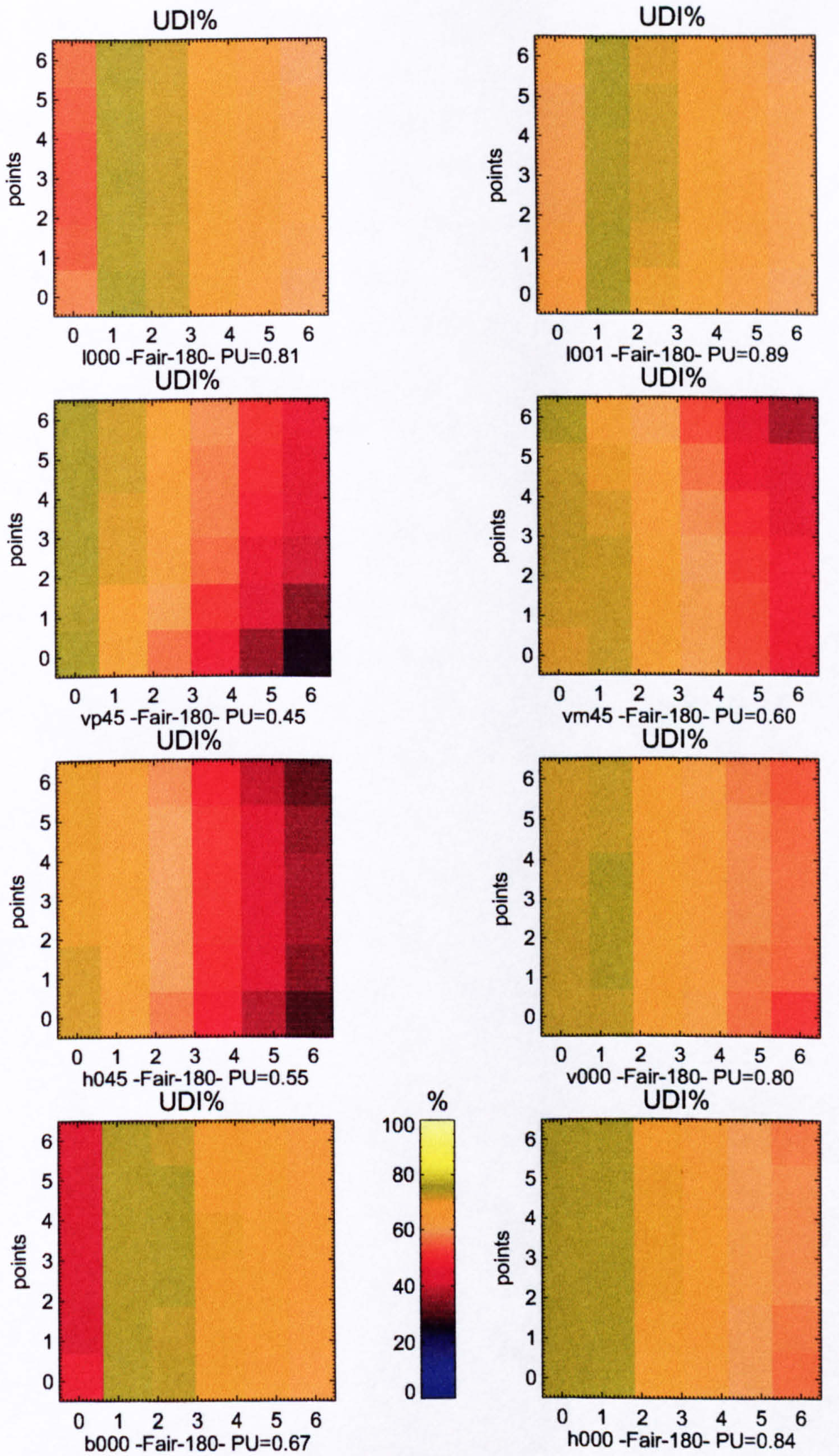

Figure A-23 UDIs point by point for Fairbanks, Alaska, U.S. (North)

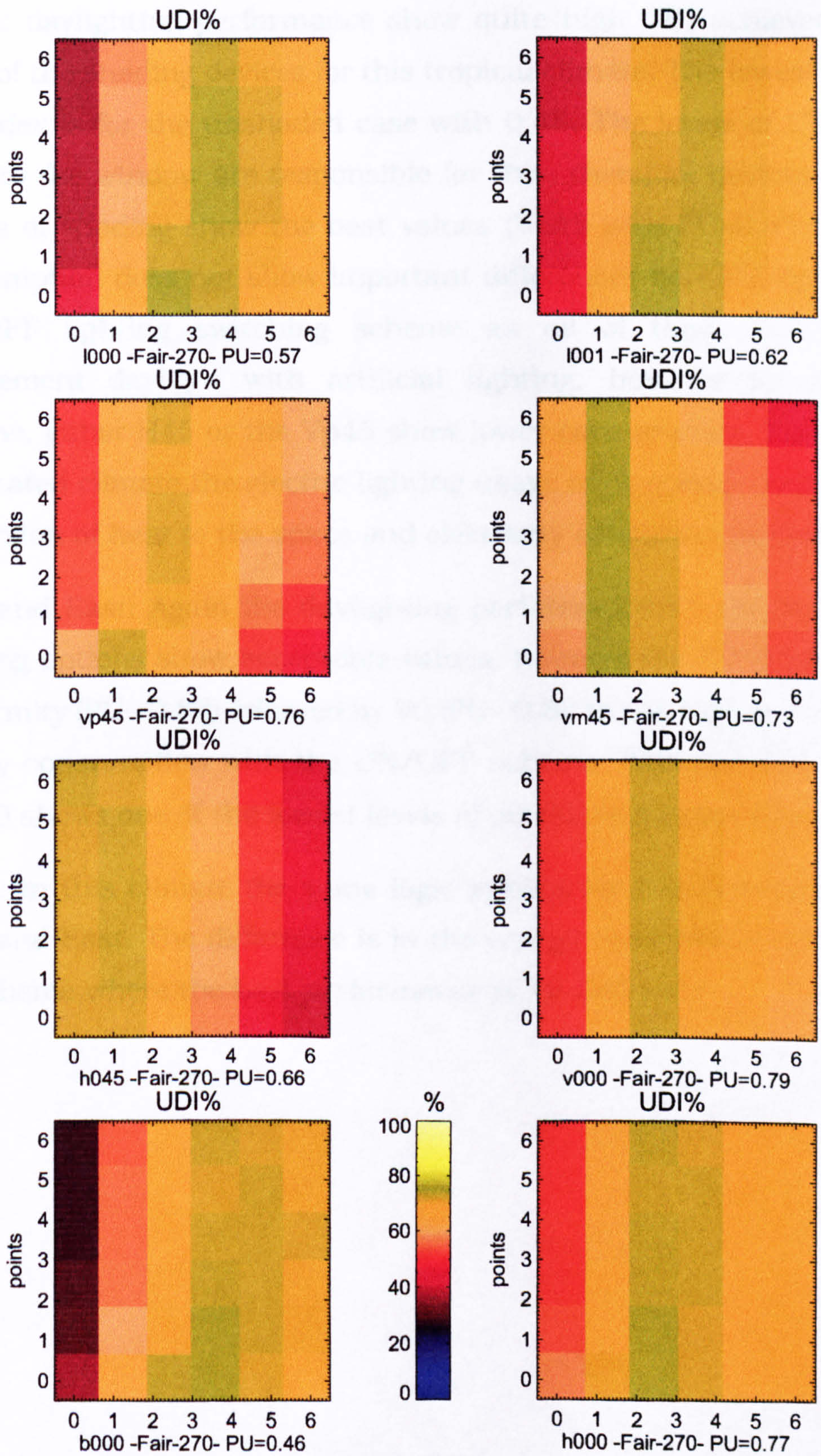

Figure A-24 UDIs point by point for Fairbanks, Alaska, U.S. (East)

A.1.7 Point by point UDIs for Guangzhou, China

South: daylighting performance show quite high UDI achieved values for most of the shading devices for this tropical climate. The lowest value of the PU index is for the unshaded case with 0.46. The levels of UDI Exceeded close to the window are responsible for this, therefore devices with a high degree of shading show the best values (Vp45 with PU=0.81). The energy consumption does not show important differences between options for the ON/OFF lighting switching scheme as all of them should need to supplement daylight with artificial lighting, however for the TOP-UP scheme, either H45 or the Vp45 show lower consumption. For this cooling dominated climate the electric lighting usage adds energy consumption via dispersion of heat to the space and electricity consumed to power lights.

West and East: Again the daylighting performance for the majority of the shading options show acceptable values, however the H0 exhibits the best uniformity (PU~ 0.83) followed by V0 (PU~ 0.8); this is reflected in the overall energy consumption with the ON/OFF scheme. With the TOP-UP scheme the V0 shows one of the lowest levels of overall energy consumption.

North: in this climate the same logic applies for this orientation than for West and East. The difference is in the energy consumption with the TOP-UP scheme where the best performance is for H45 case.

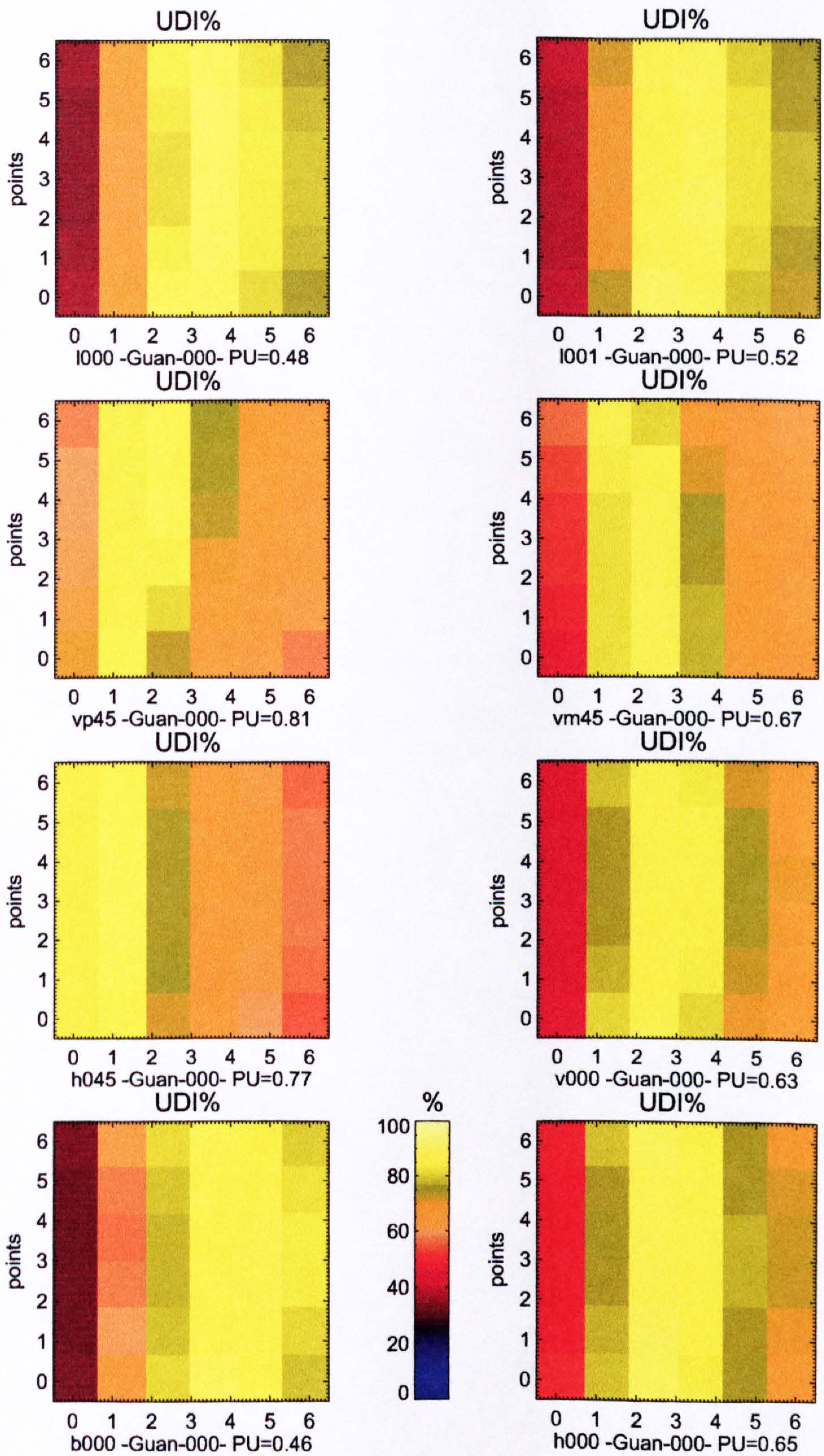

Figure A-25 UDIs point by point for Guangzhou, China (South)

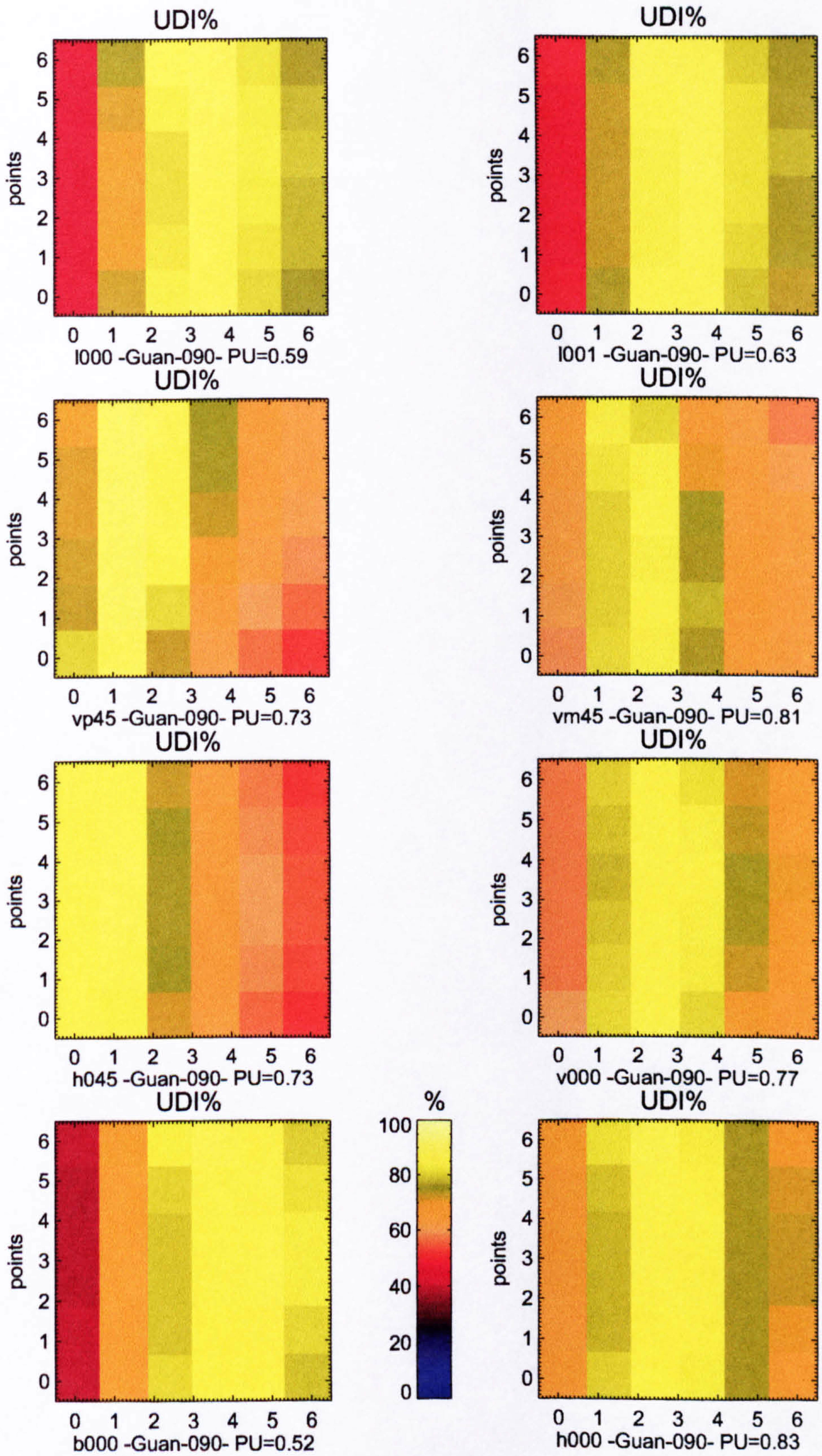

Figure A-26 UDIs point by point for Guangzhou, China (West)

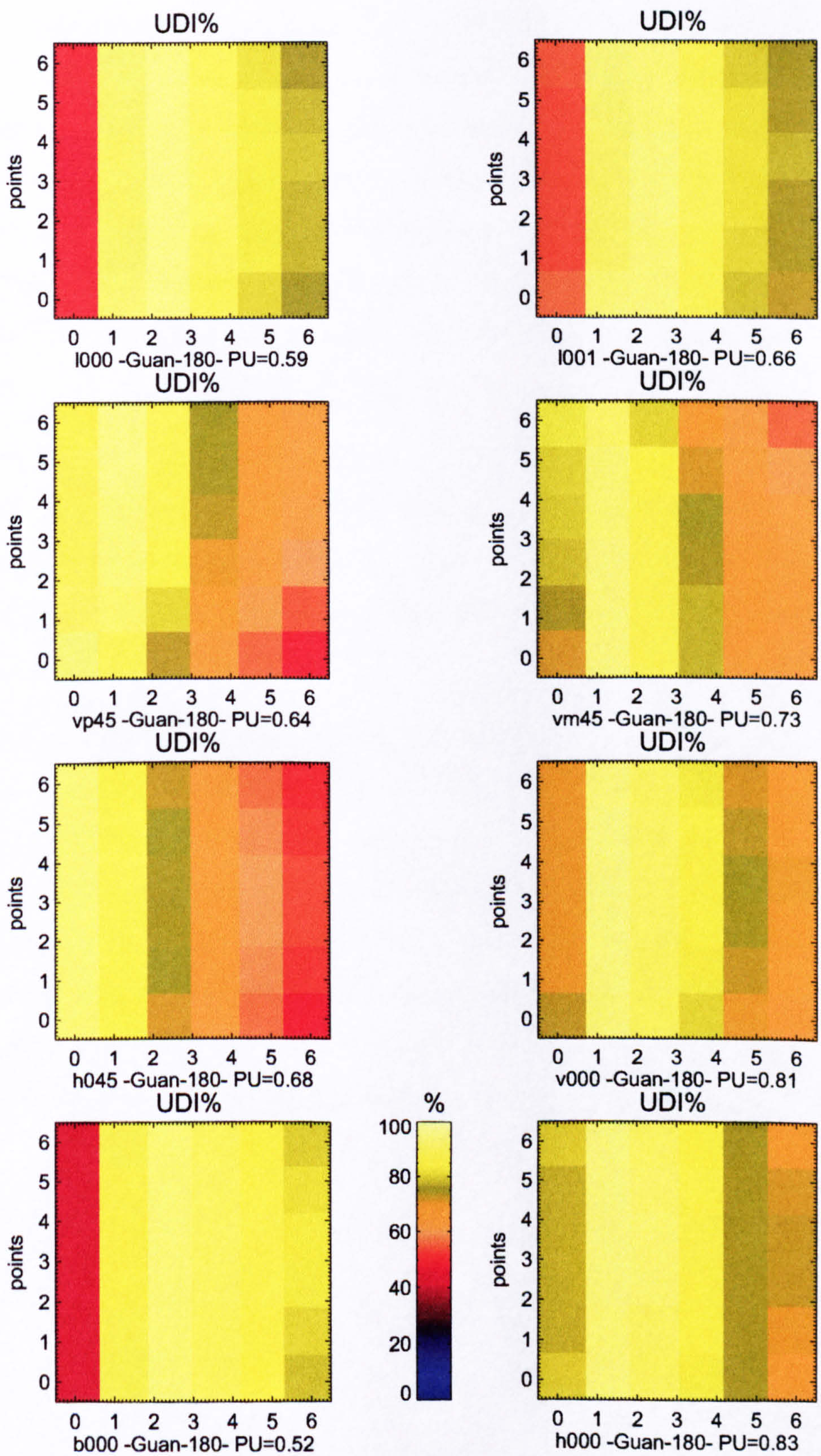

Figure A-27 UDIs point by point for Guangzhou, China (North)

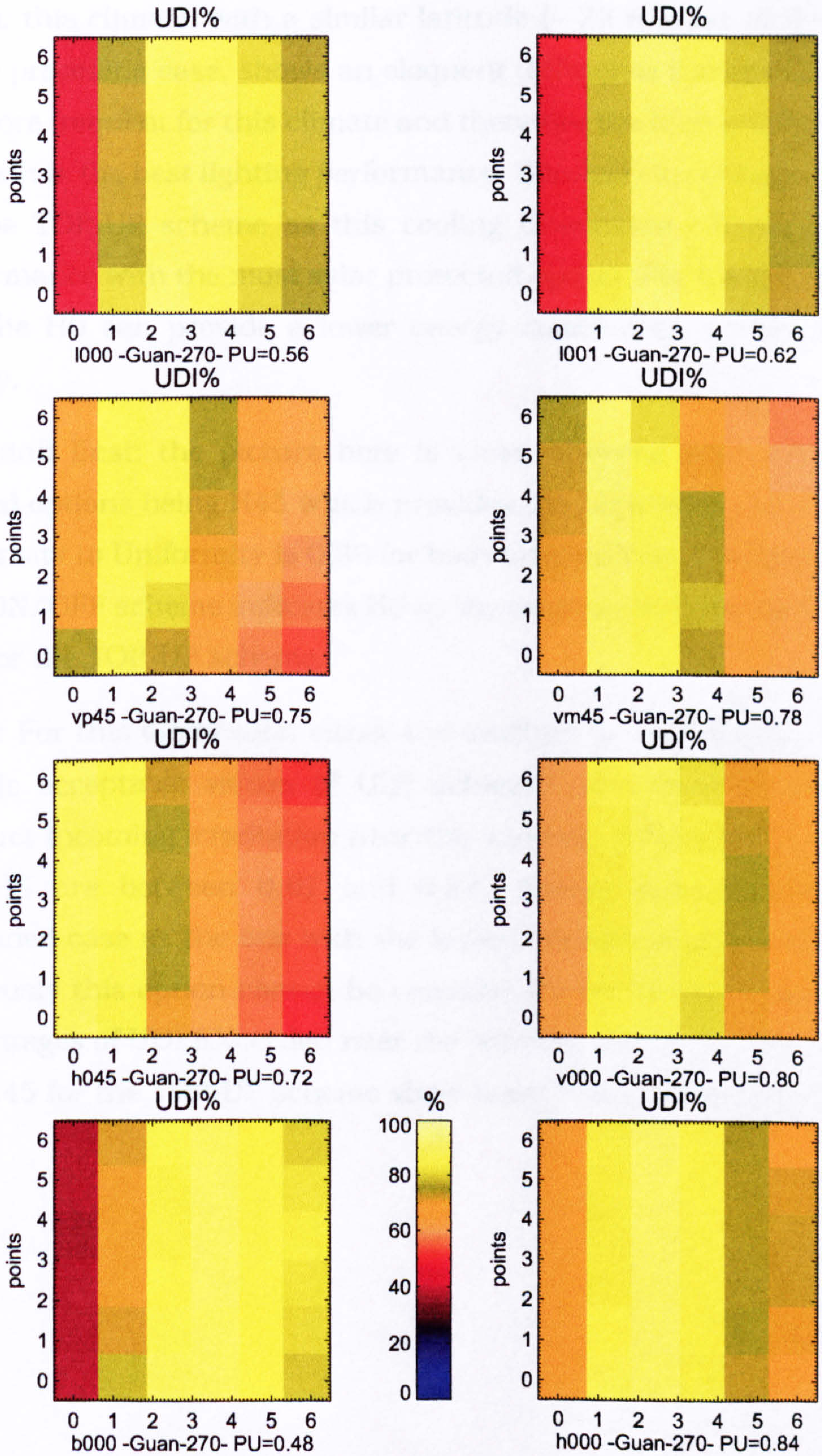

Figure A-28 UDIs point by point for Guangzhou, China (East)

A.1.8 Point by point UDIs for Havana, Cuba

South: this climate, with a similar latitude (~ 23 degrees of North latitude) to the preceding case, shows an eloquent difference though. UDI Exceeded are more frequent for this climate and therefore the high shaded option H45 can deliver the best lighting performance. Similarly for energy consumption for the TOP-UP scheme as this cooling dominated climate improves its performance with the most solar protected option. For the ON/OFF scheme still the H0 can provide a lower energy consumption using less cooling energy.

West and East: the picture here is clear, showing a prevalence of high shaded options being H45 which provides the high values of UDI achieved. Propensity to Uniformity is 0.86 for both orientations. Energy consumption with ON/OFF scheme indicates H0 as the example with the lowest value and H45 for the TOP-UP scheme.

North: For this orientation either the medium or high shaded options can provide acceptable values of UDI achieved, low shaded options cannot obstruct incoming irradiation near the window. Values of PU index for MS and HS are between 0.67 and 0.84. Energy consumption shows an unshaded case as the one with the lowest consumption however as stated previously this option cannot be considered - on its own - due to the high percentages of UDI EXceeded near the window. H0 for the ON/OFF scheme and H45 for the TOP-UP scheme show lower energy consumption figures

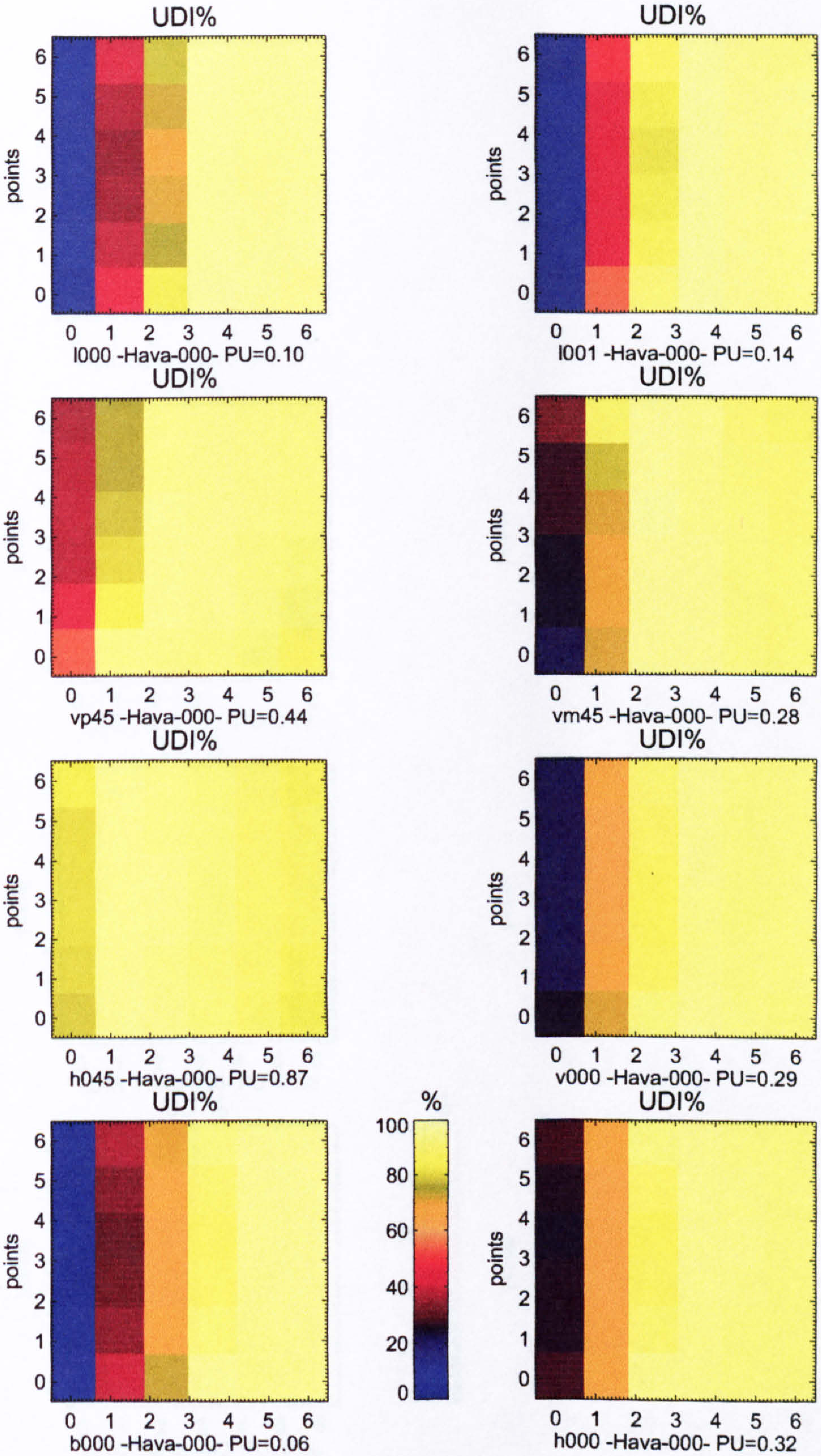

Figure A-29 UDIs point by point for Havana, Cuba (South)

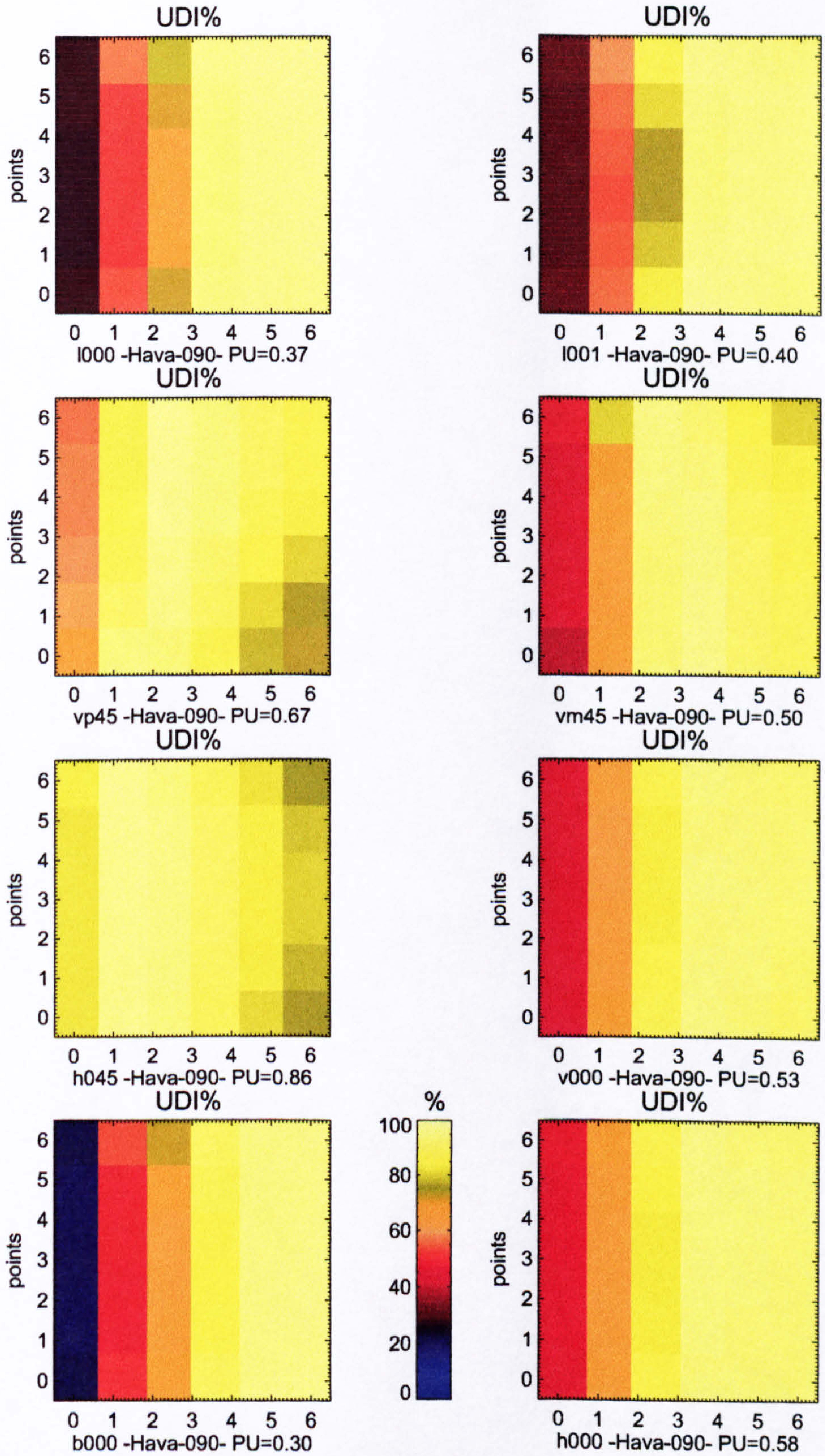

Figure A-30 UDIs point by point for Havana, Cuba (West)

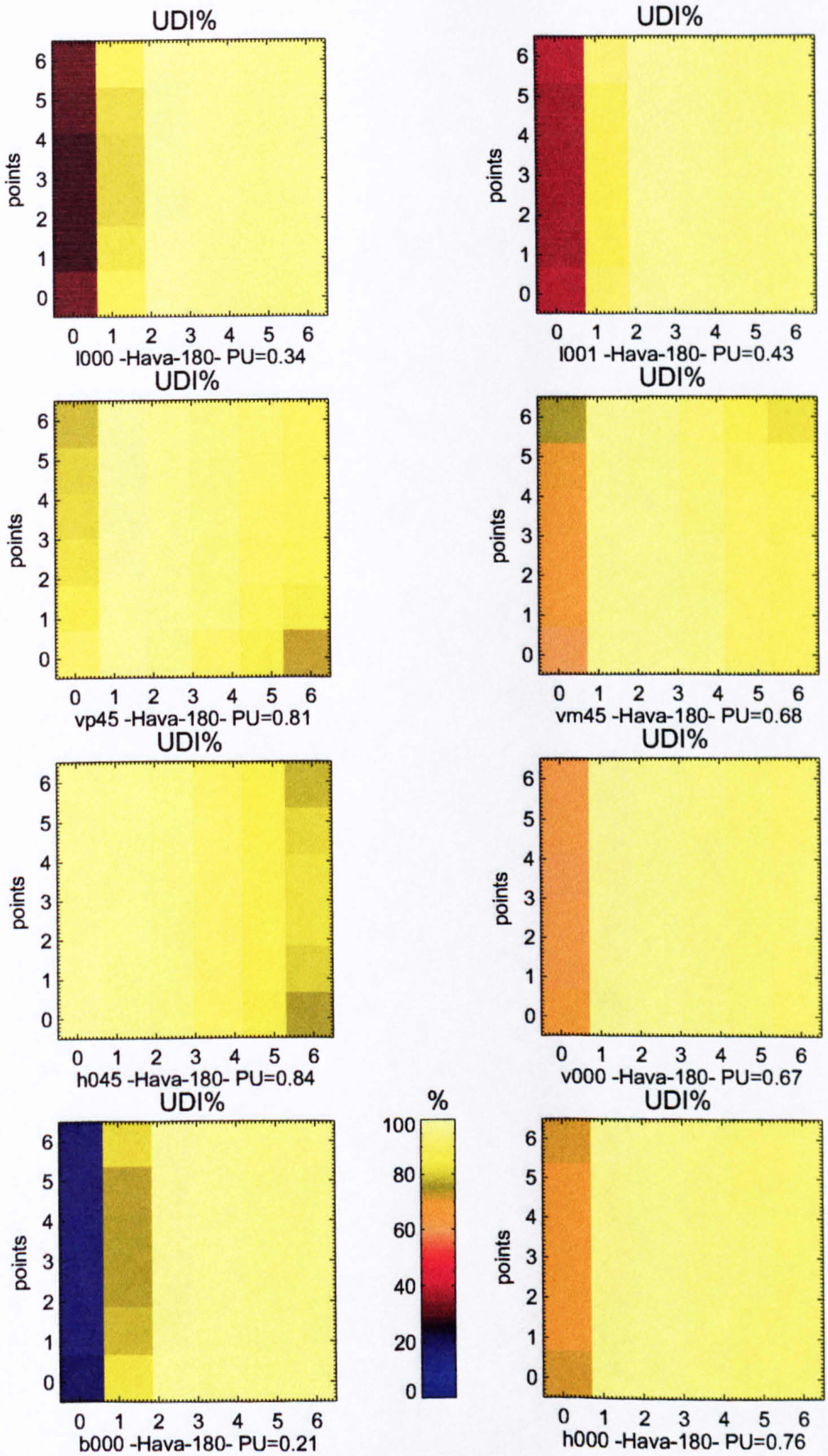

Figure A-31 UDIs point by point for Havana, Cuba (North)

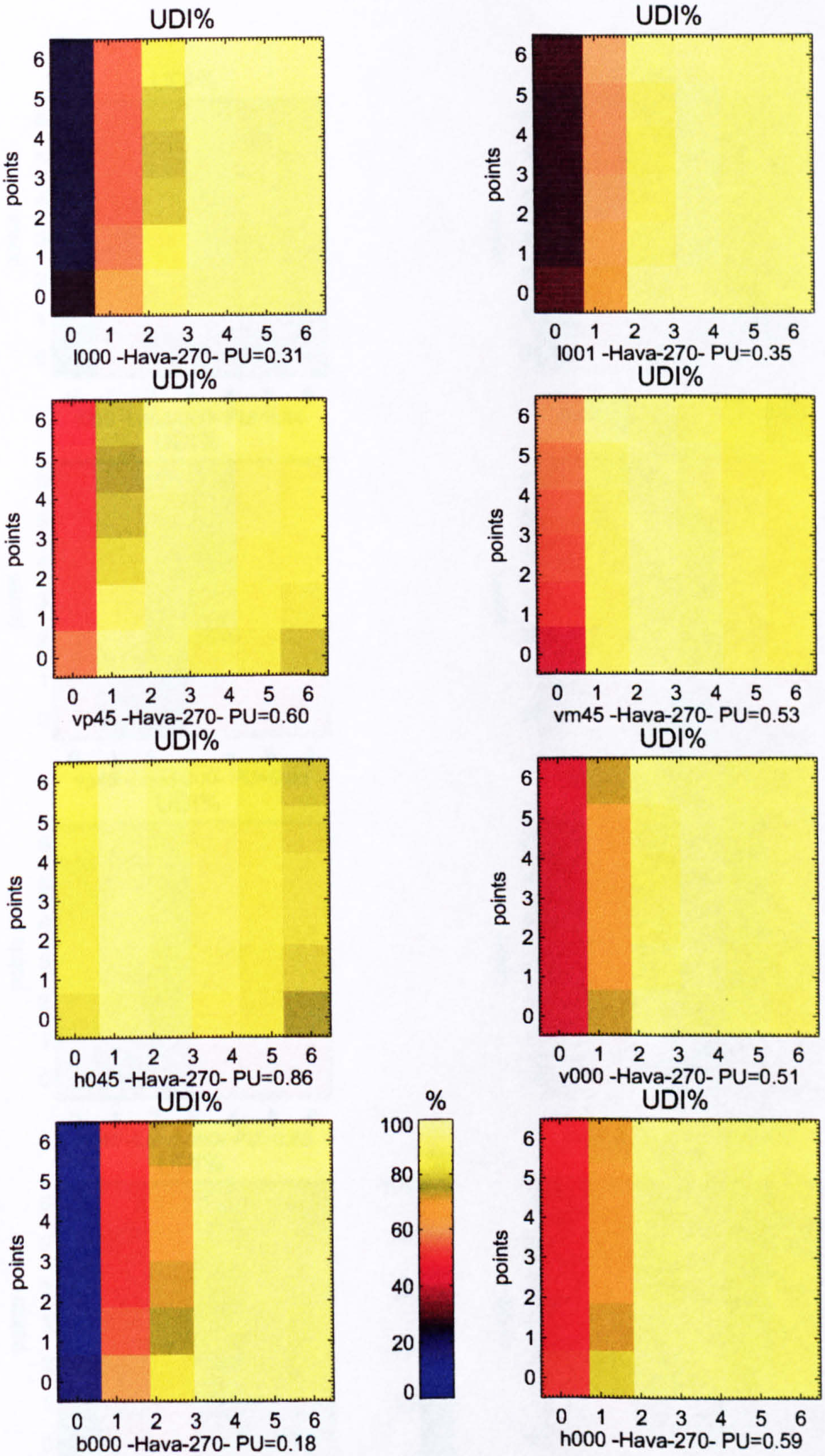

Figure A-32 UDIs point by point for Havana, Cuba (East)

A.1.9 Point by point UDIs for London, United Kingdom

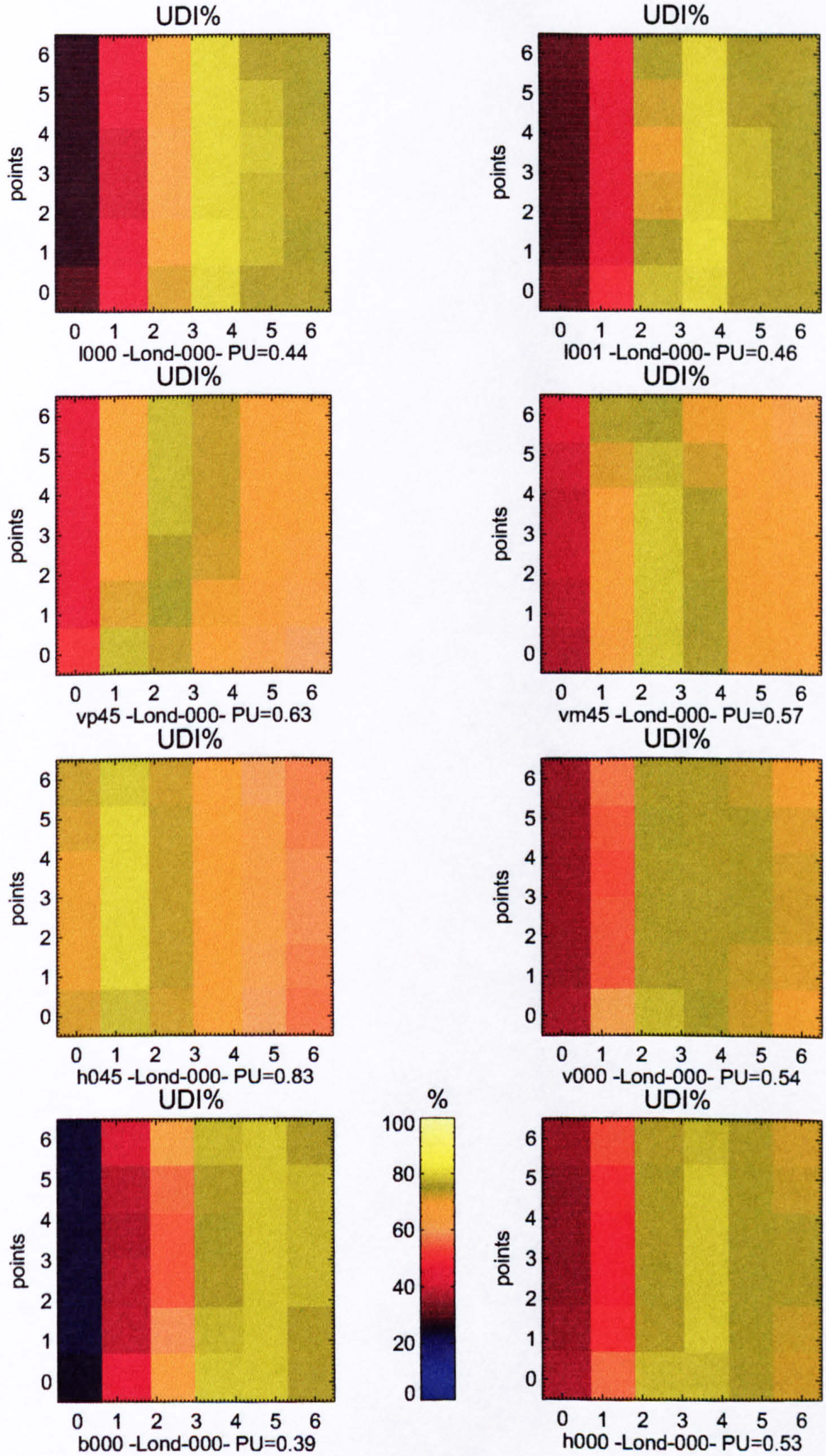

Figure A-33 UDIs point by point for London, United Kingdom (South)

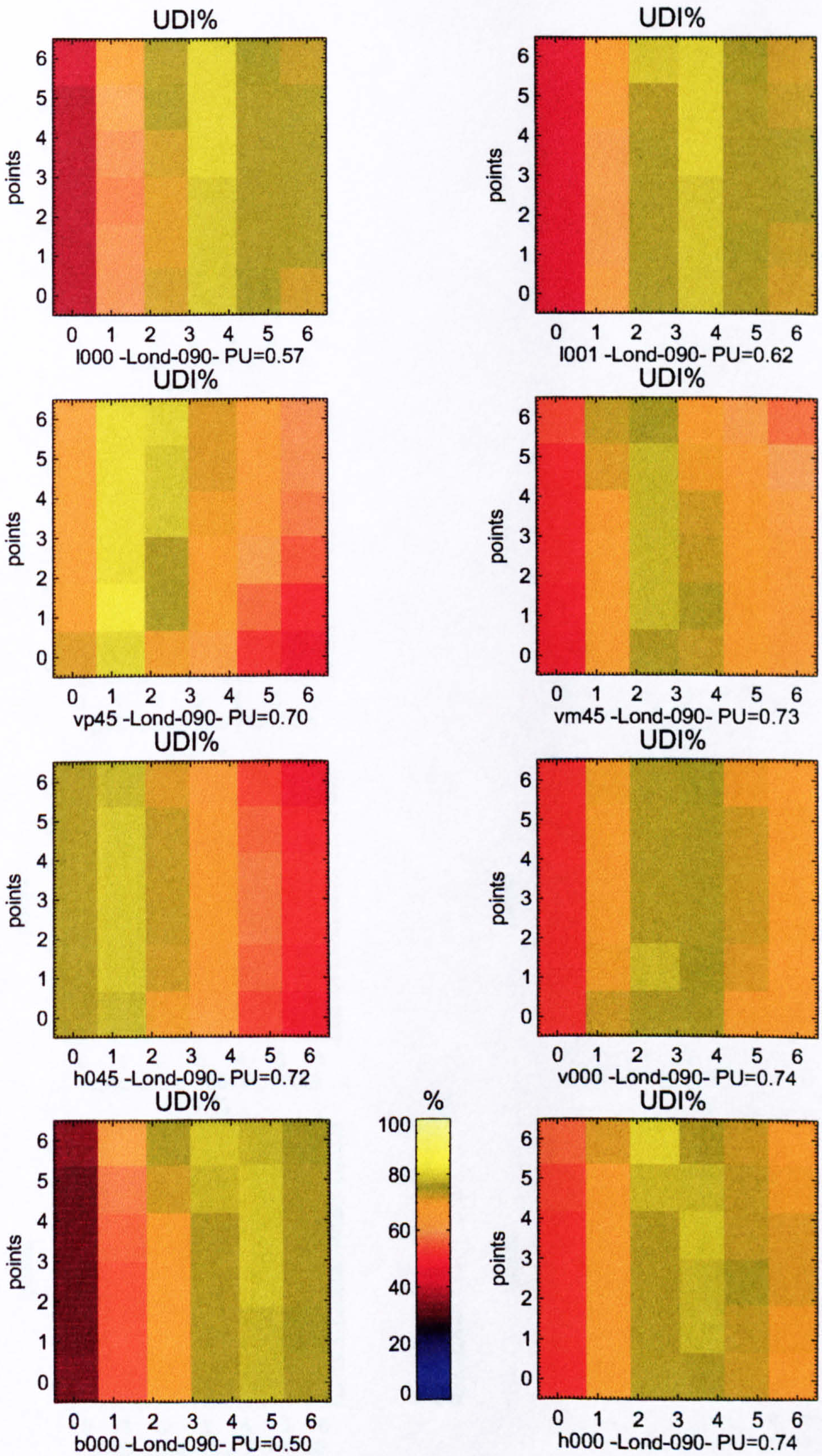

Figure A-34 UDIs point by point for London, United Kingdom (West)

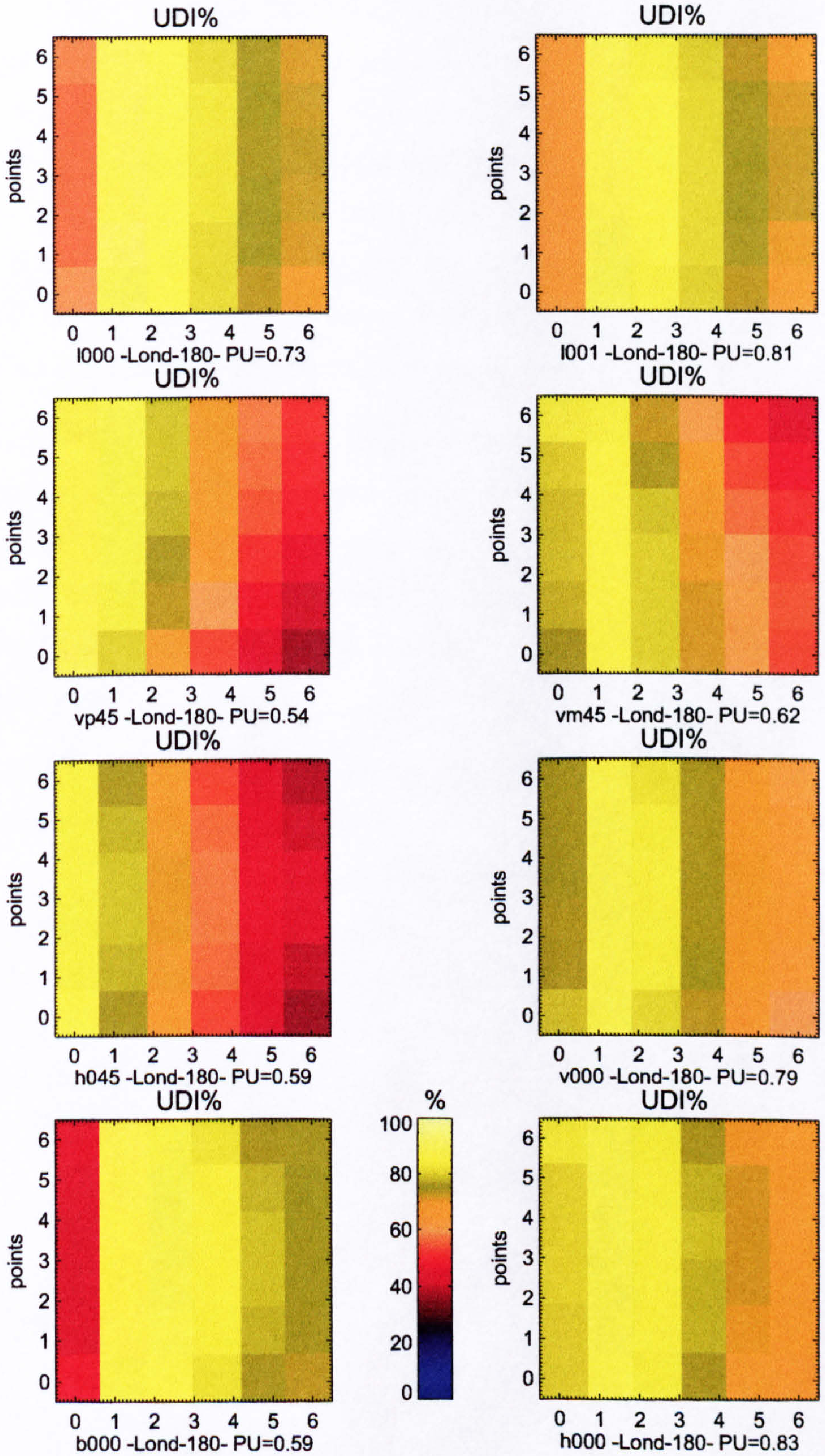

Figure A-35 UDIs point by point for London, United Kingdom (North)

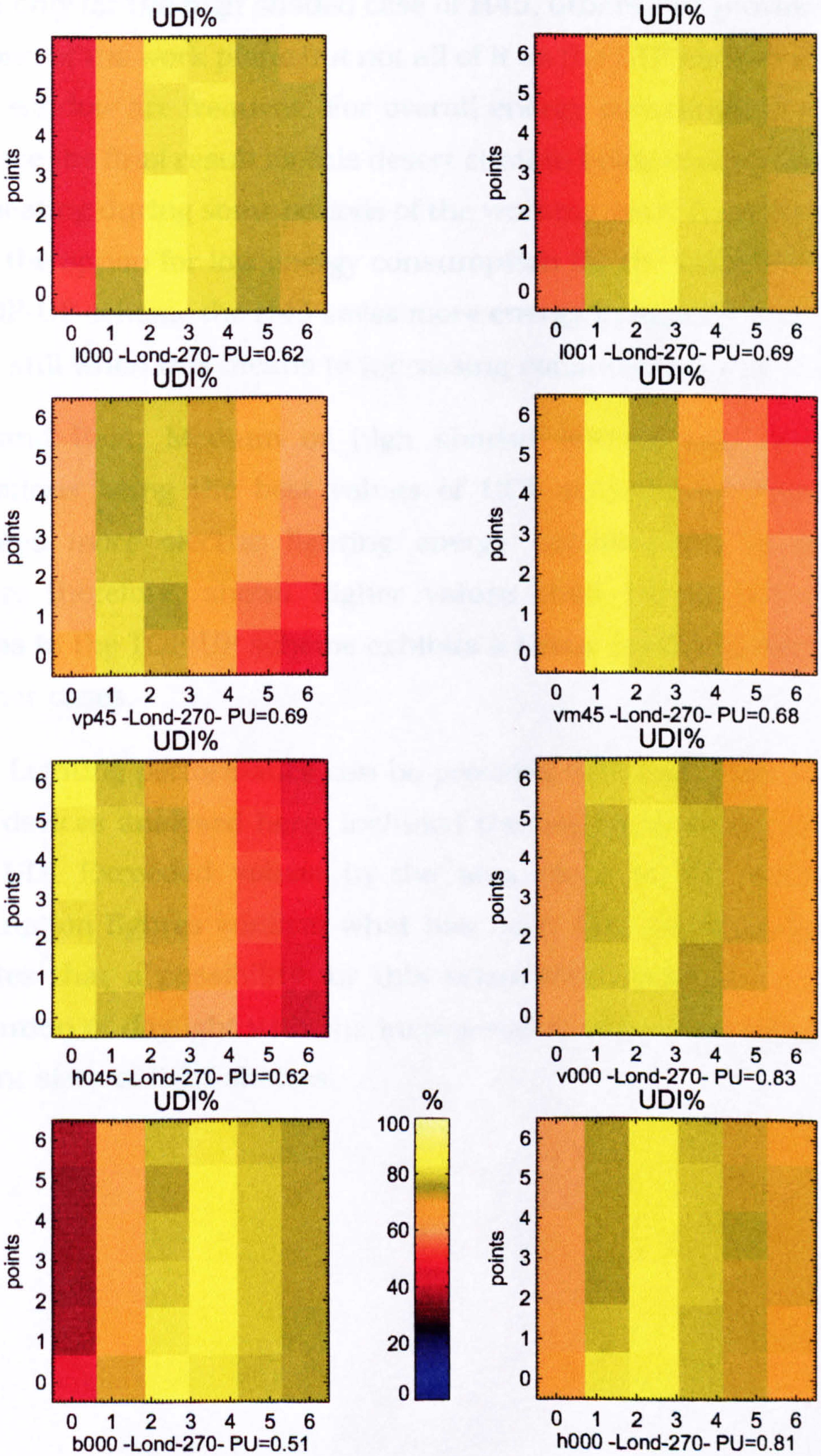

Figure A-36 UDIs point by point for London, United Kingdom (East)

A.1.10 Point by point UDIs for Murcia, Spain

South: Daylighting performance shows UDI achieved values with acceptable values only for the high shaded case of H45, others can provide high values for a part of the work plane but not all of it as the UDI exceeded values close to the window are frequent. For overall energy consumption many factors influence the final result as this desert climate being cooling dominated still uses heating during some periods of the working year. Therefore, it presents H0 as the option for low energy consumption for the ON/OFF scheme. For the TOP-UP scheme the H45 saves more energy in lighting and cooling than others still when this means to increasing consumption due to heating.

West and East: Medium or high shaded options can cater for these orientations being the best values of UDI achieved for H45. The latter generates more electric lighting energy consumption in the ON/OFF scheme, therefore, shows higher values than H0 or the light-shelves whereas in the TOP-UP scheme exhibits a better performance than most of the other cases.

North: Lighting performance can be provided with high standards by most of the devices analysed here, included the low shaded options if they can avoid UDI Exceeded values in the area close to the window. Energy consumption figures confirm what has been said about daylighting. This indicates that a possibility for this orientation could be to improve the distribution of daylight with the incorporation of internal blinds or testing different sizes of light-shelves.

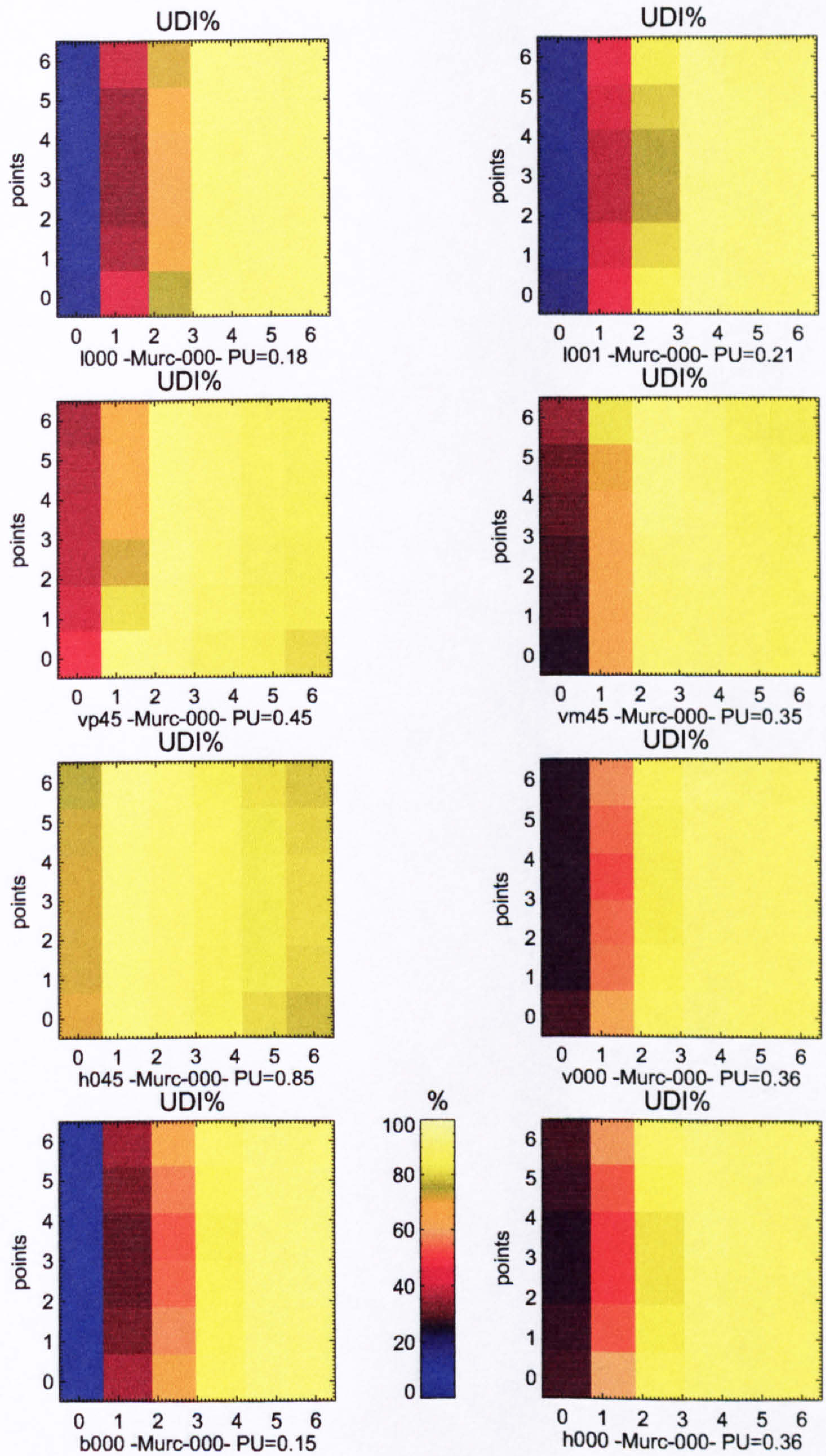

Figure A-37 UDIs point by point for Murcia, Spain (South)

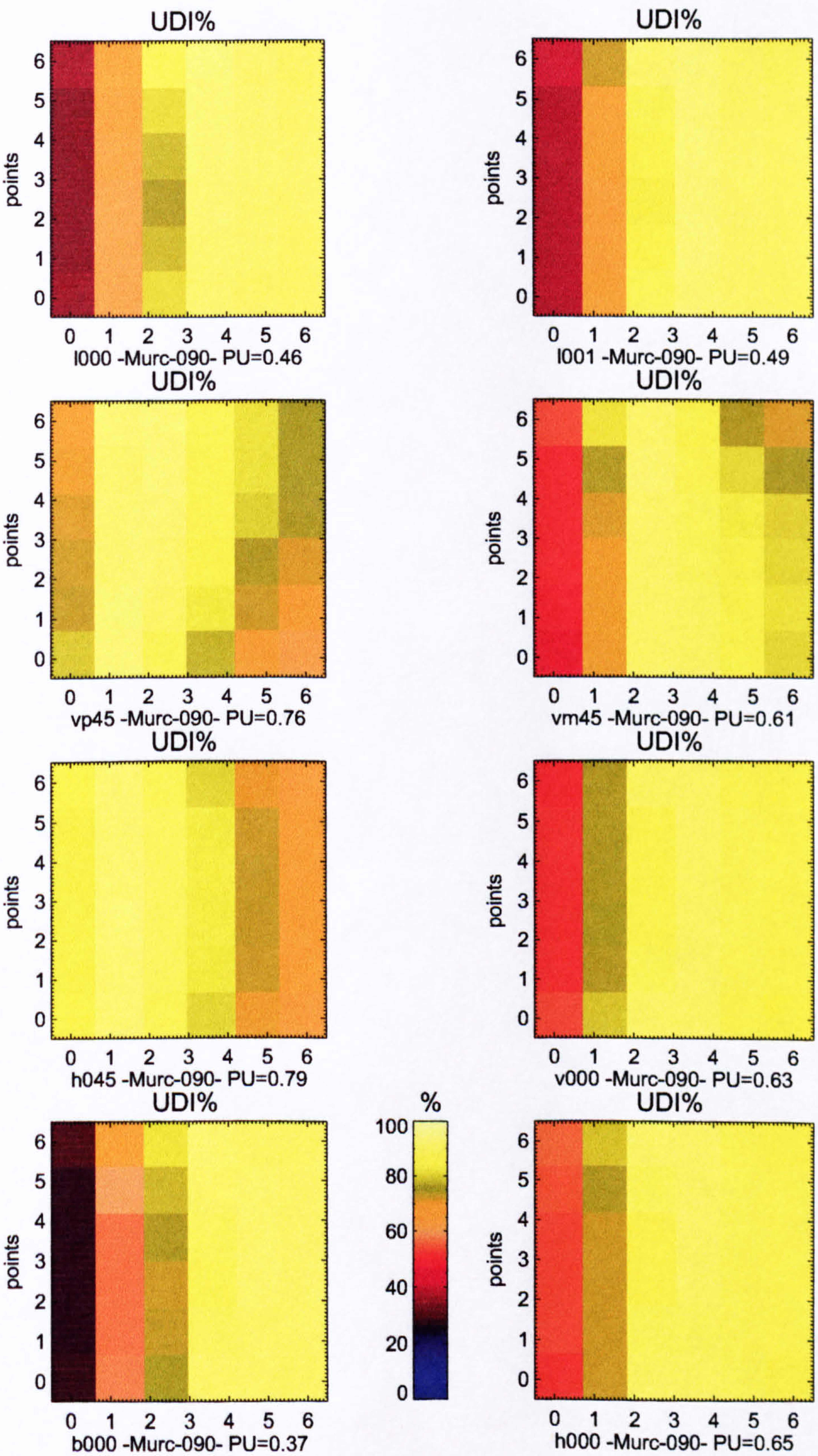

Figure A-38 UDIs point by point for Murcia, Spain (West)

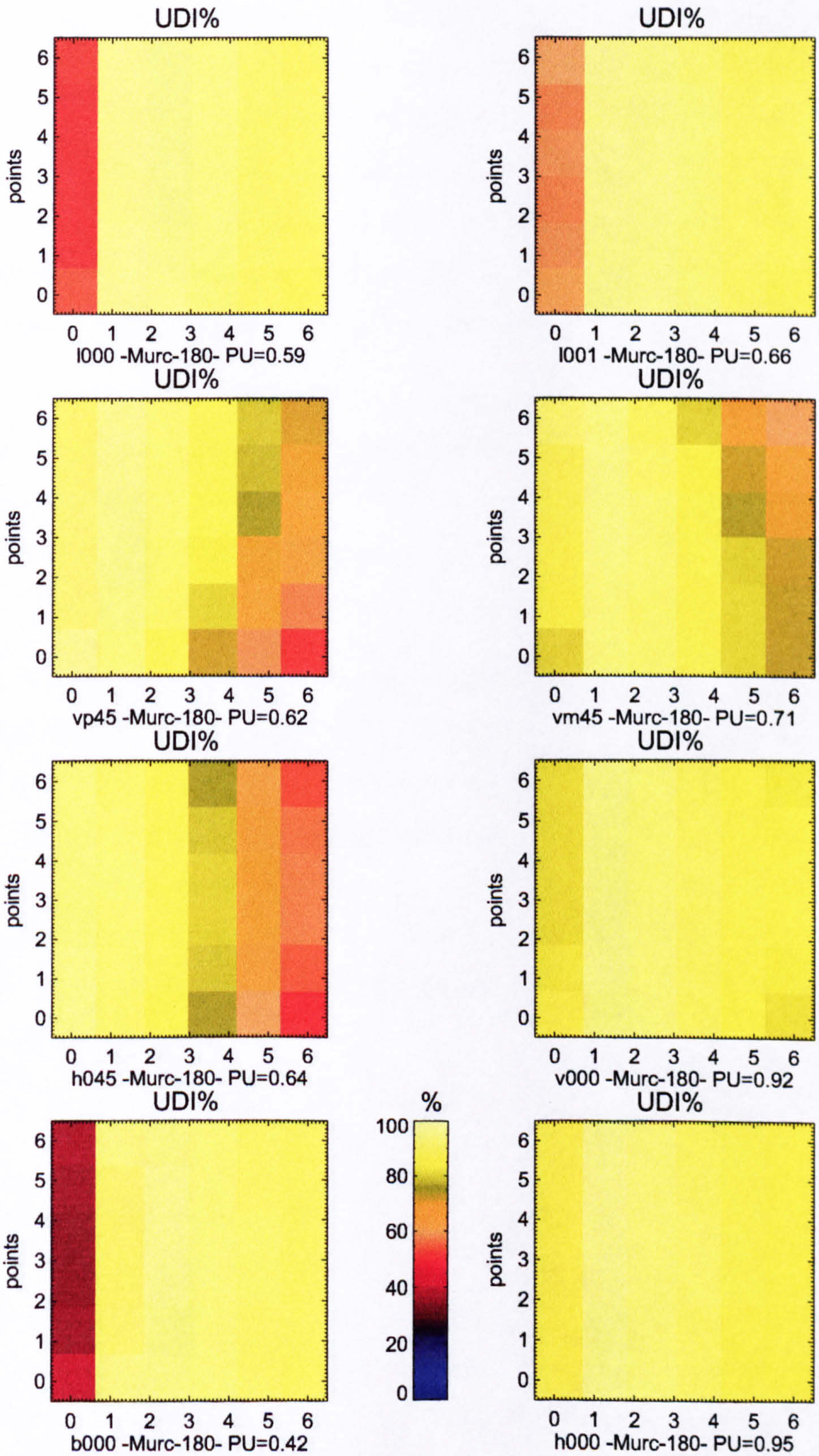

Figure A-39 UDIs point by point for Murcia, Spain (North)

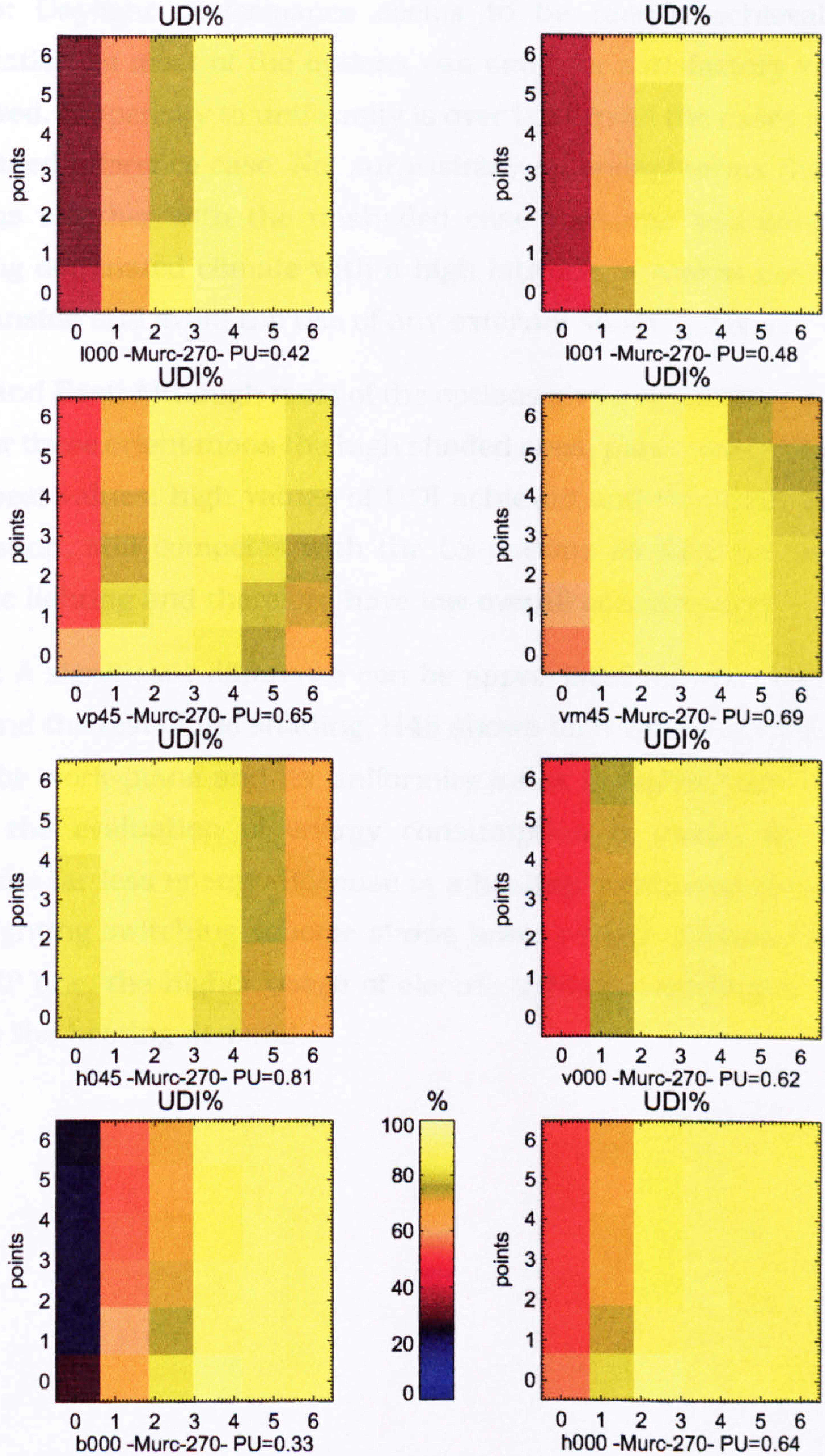

Figure A-40 UDIs point by point for Murcia, Spain (East)

A.1.11 Point by point UDIs for Punta Arenas, Chile

South: Daylight performance seems to be readily achievable for this orientation as most of the options can cater for satisfactory values of UDI achieved. Propensity to uniformity is over 0.57 in all the cases including the unshaded reference case. Not surprisingly, in energy terms the low shaded options together with the unshaded case consume less energy. Being a heating dominated climate with a high latitude, it makes easier to control glare inside and avoid the use of any external shading device.

West and East: Although most of the options give a reasonable performance, still for these orientations the high shaded ones, particularly Vm45 provides with best values: high values of UDI achieved and PU=0.78. In the energy evaluation, still competes with the LS options as they do not use much electric lighting and therefore have low overall consumption.

North: A significant difference can be appreciated between a HS option as H45 and the rest of the shading, H45 shows high values of UDI achieved all over the work-plane and its uniformity index is higher than 0.8. However when the evaluation of energy consumption is made, the LS options consume far less energy. Because is a heating dominated climate the ON/OFF lighting switching scheme shows lower energy consumption than the TOP-UP one, the higher usage of electric lighting contributes in a positive way to the heating demand.

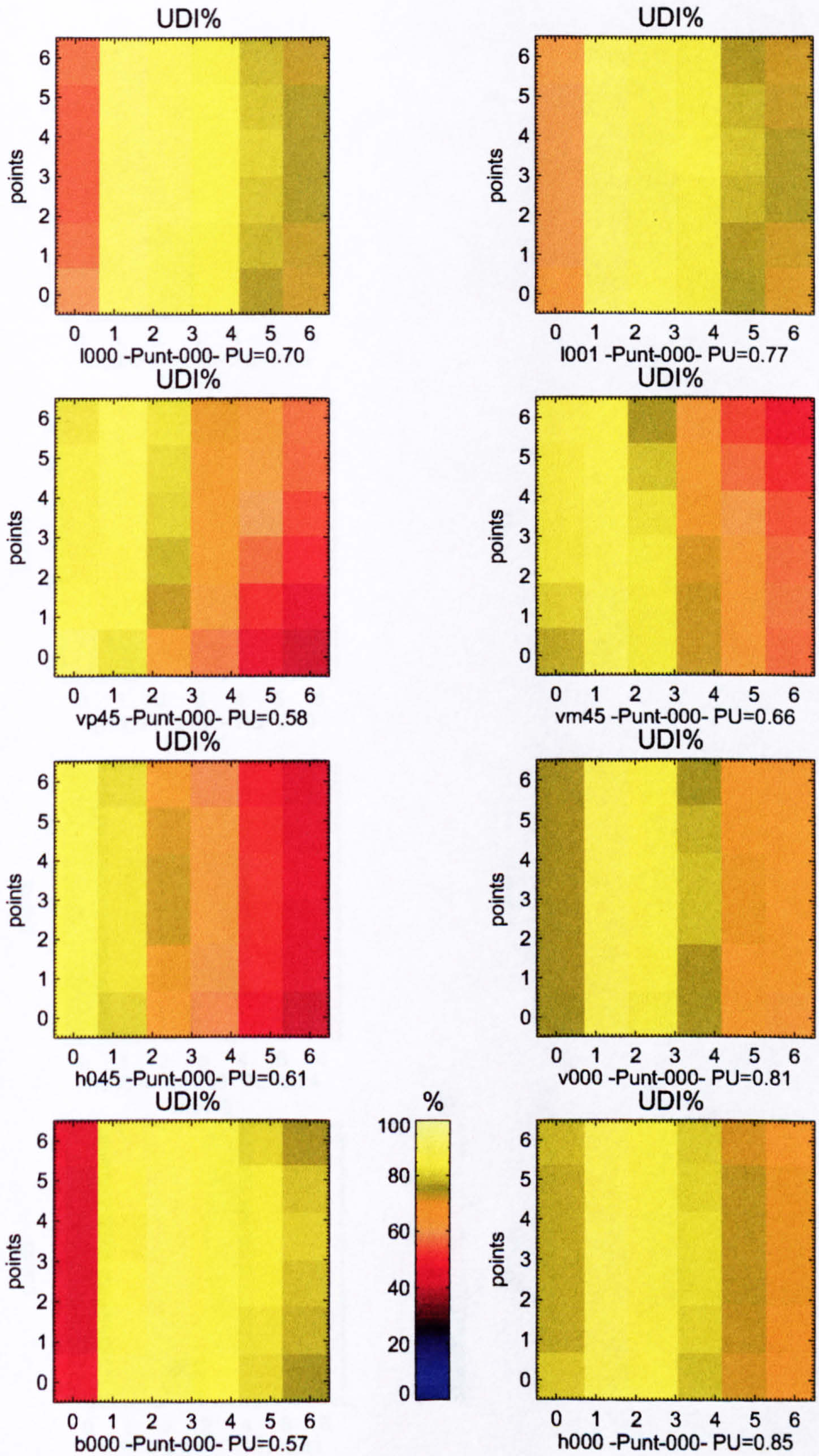

Figure A-41 UDIs point by point for Punta Arenas, Chile (South)

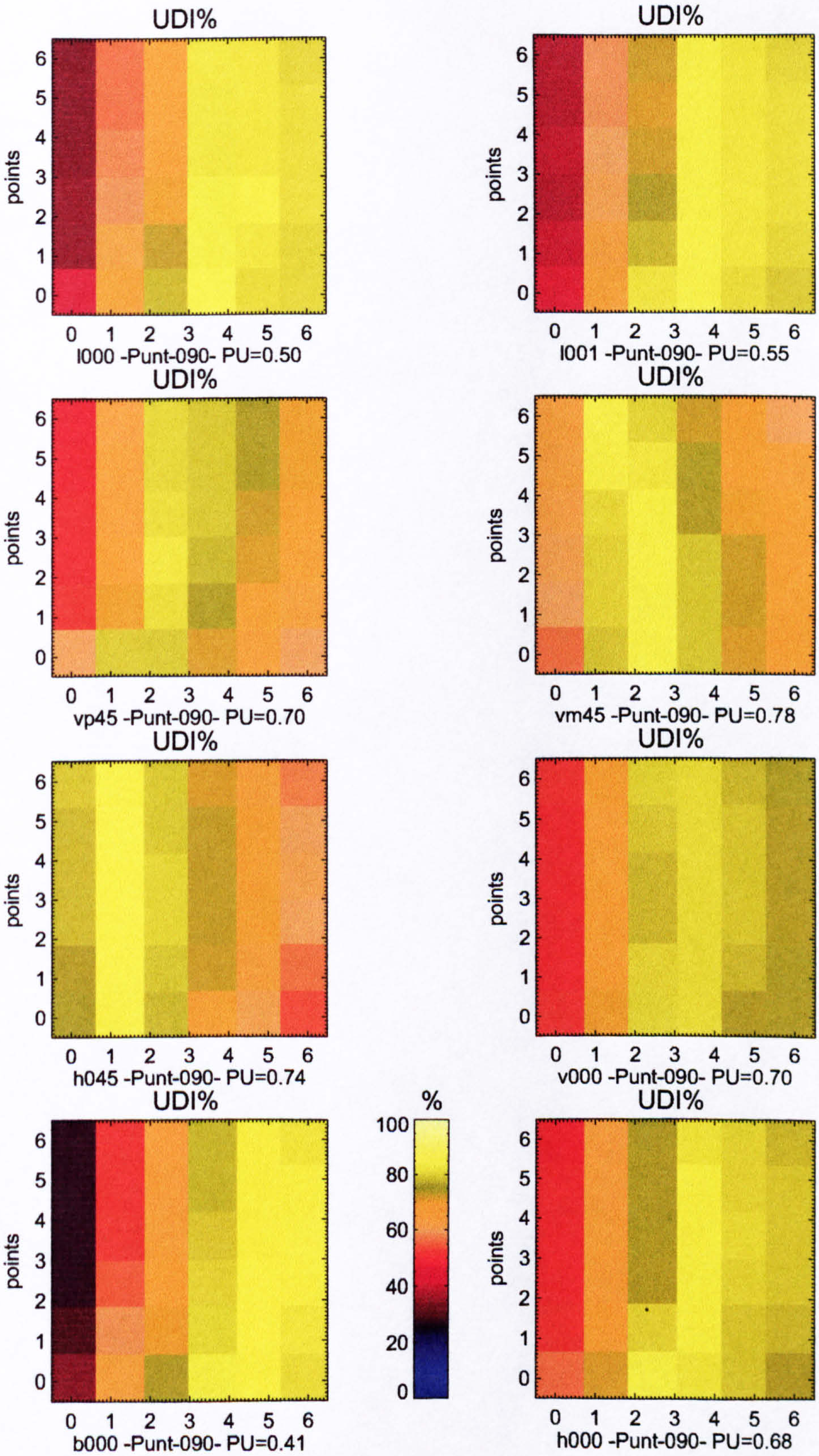

Figure A-42 UDIs point by point for Punta Arenas, Chile (West)

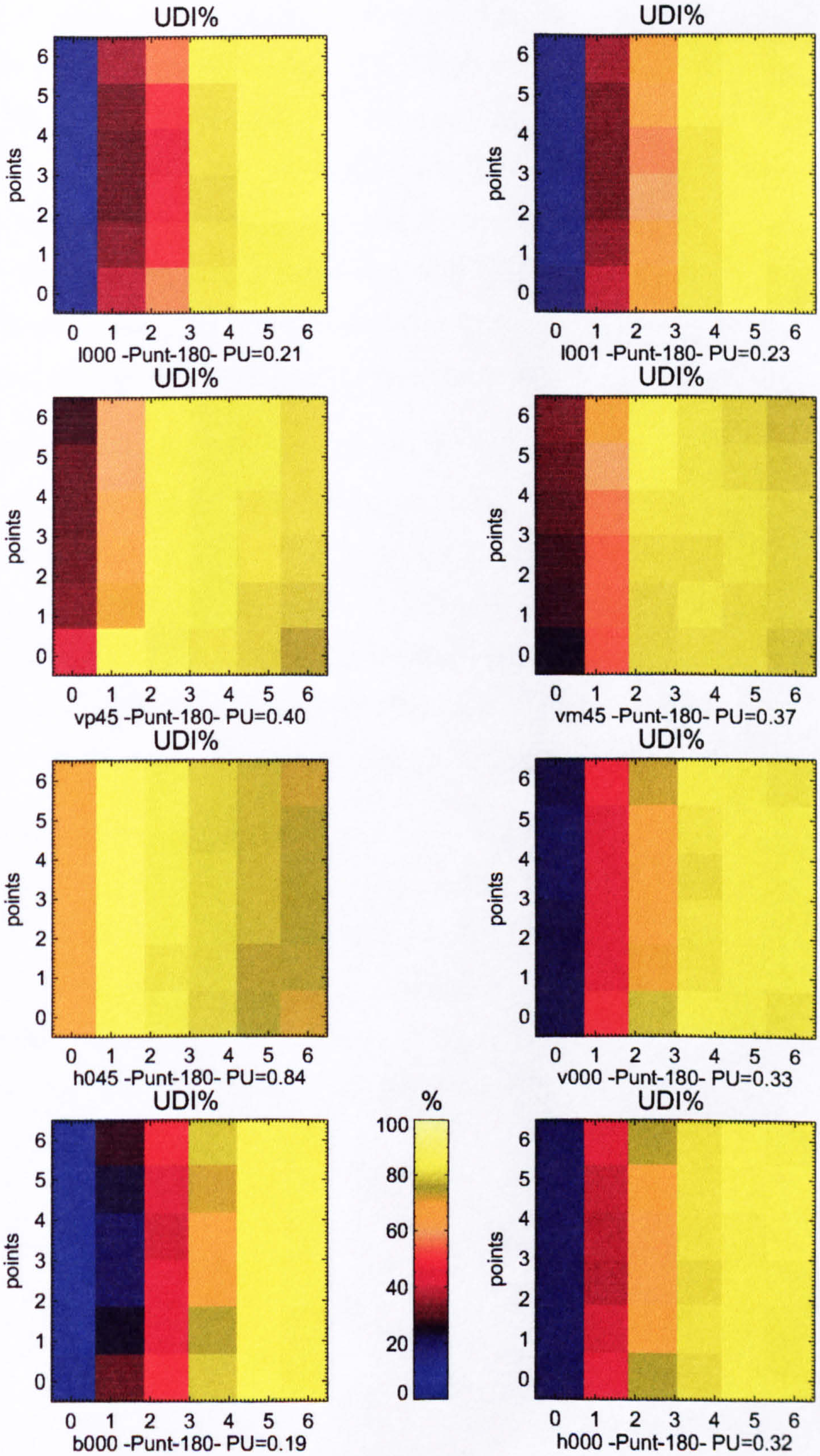

Figure A-43 UDIs point by point for Punta Arenas, Chile (North)

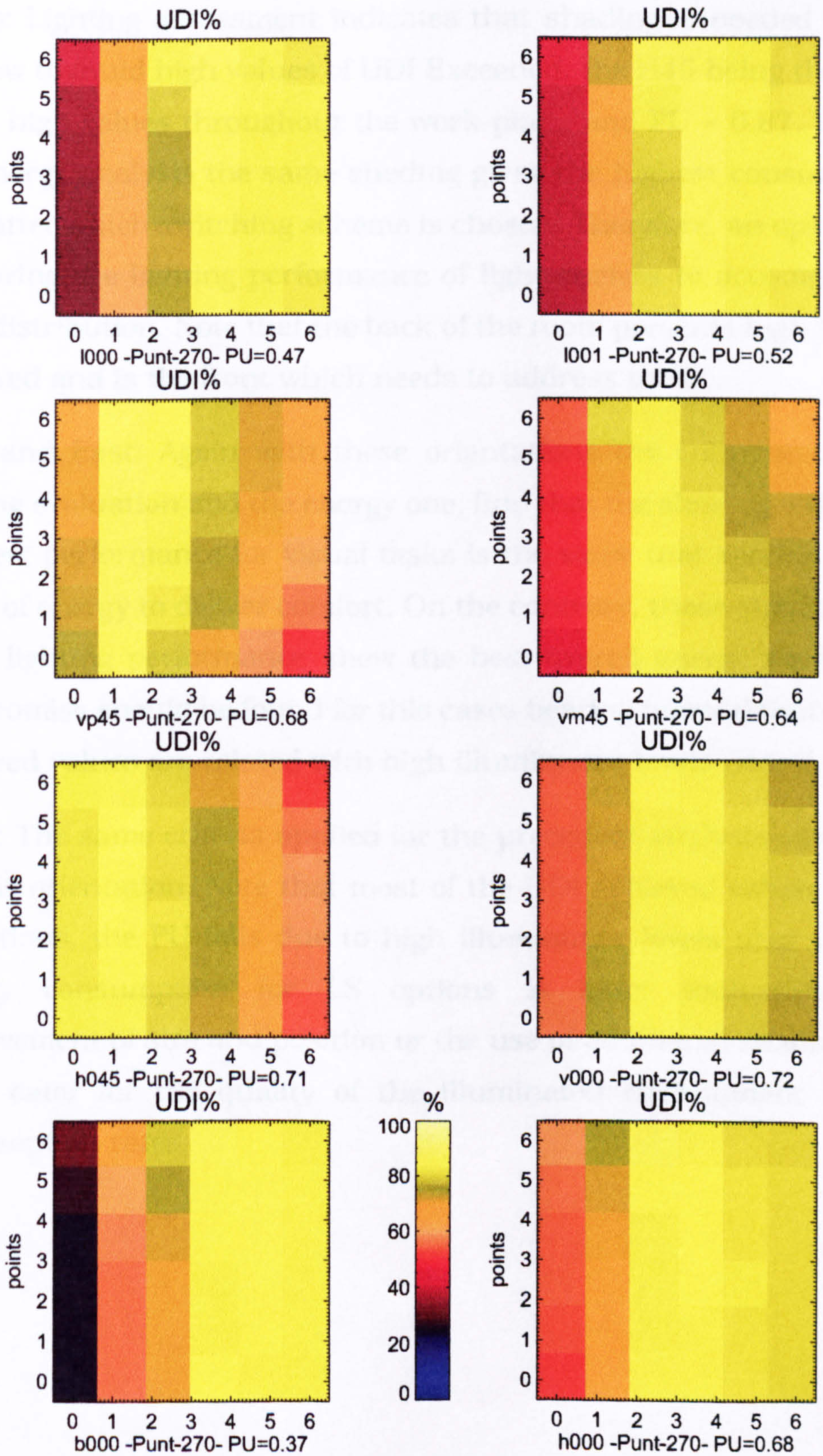

Figure A-44 UDIs point by point for Punta Arenas, Chile (East)

A.1.12 Point by point UDIs for Sapporo, Japan

South: Lighting assessment indicates that shading is needed close to the window to avoid high values of UDI Exceeded, the H45 being the one which offers high values throughout the work-plane and PU = 0.87. However, for the energy analysis the same shading gives the highest consumption level no matter which switching scheme is chosen. Therefore, an option could be improving the lighting performance of light-shelves to accomplish a more even distribution. Note that the back of the room presents high levels of UDI achieved and is the front which needs to address them.

West and East: Again with these orientations the contrast between the lighting evaluation and the energy one, find that the shading which predicts the best performance for visual tasks is the same that spends the highest levels of energy to deliver comfort. On the contrary, those shadings with the lower lighting performance show the best overall energy performance. A compromise should be found for this cases bearing in mind that the low UDI achieved values are related with high illuminance levels near the window.

North: The same criteria applied for the precedent analysis can be applied for this orientation. Note that most of the UDI achieved values are high in LS options, the PU falls due to high illuminance levels near the window. Energy consumption for LS options is lower indicating that the improvement of size and position or the use of additional shading - interior - will cater for the quality of the illuminated environment and energy consumption rates.

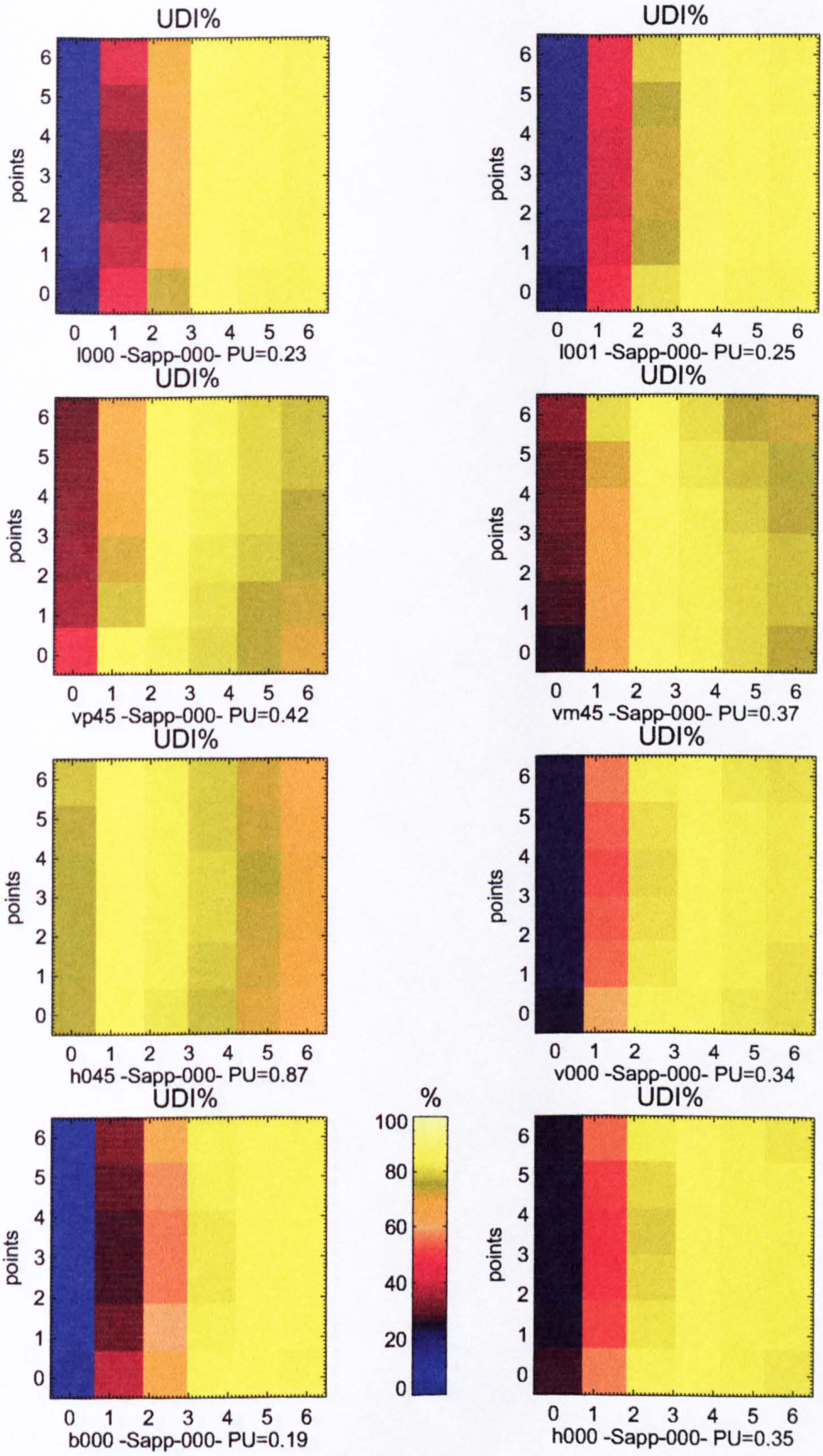

Figure A-45 UDIs point by point for Sapporo, Japan (South)

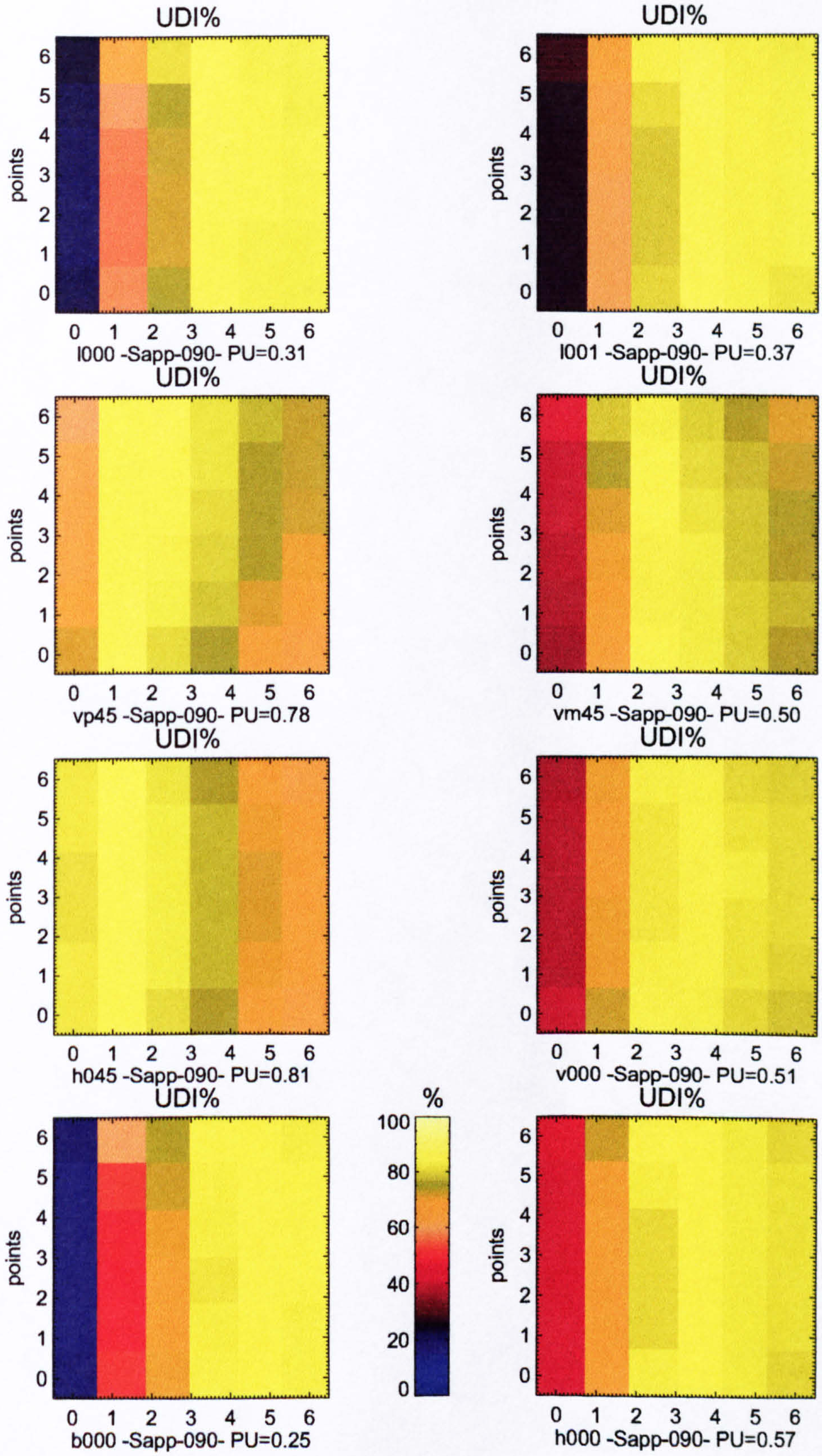

Figure A-46 UDIs point by point for Sapporo, Japan (West)

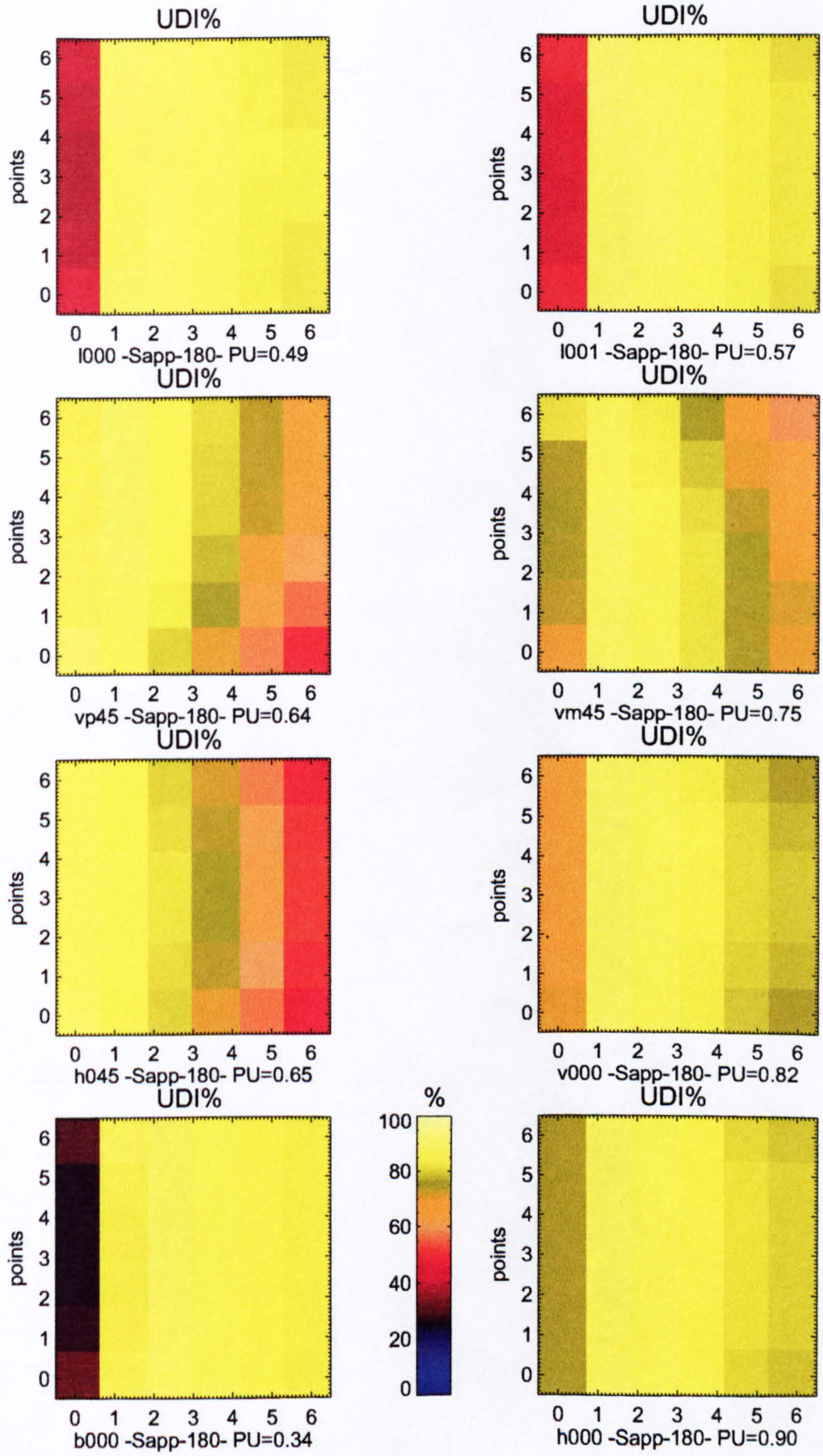

Figure A-47 UDIs point by point for Sapporo, Japan (North)

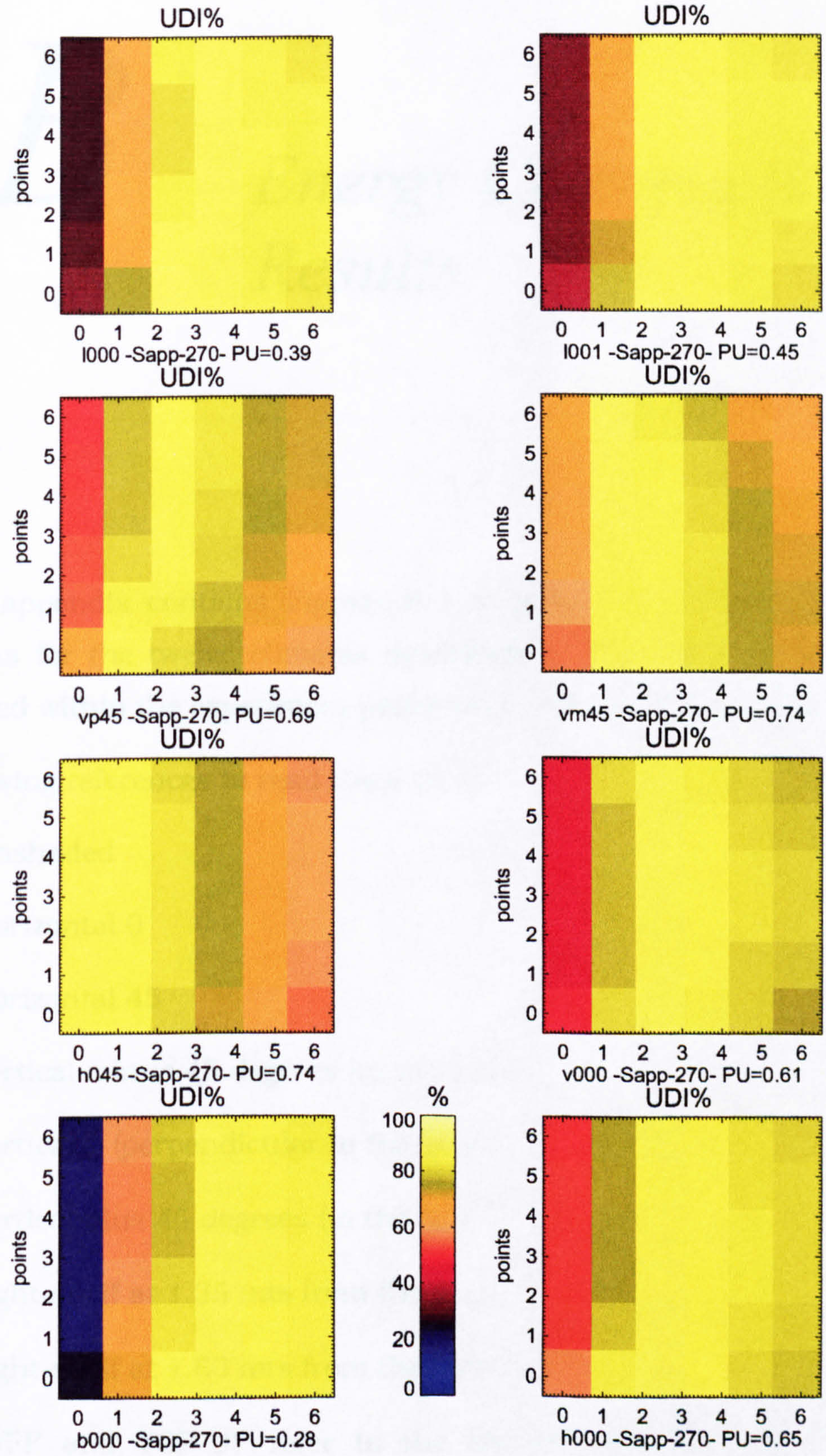

Figure A-48 UDIs point by point for Sapporo, Japan (East)

Appendix

B

Energy Consumption Results

This appendix contains Figures B-1 to B-12 with Energy Consumption results for the twelve climates described in Figure 5-2 which have been studied within the experiment performed with HyDiLM in Chapter 5.

Following references to read these plots :

0 - Unshaded

1 - Horizontal 0

2 - Horizontal 45

3 - Vertical minus 45 degrees (to the right)

4 - Vertical 0 (perpendicular to the glass)

5 - Vertical plus 45 degrees (to the left)

6 - Light-shelf at 1.35 mts from the floor

7 - Light-shelf at 1.60 mts from the floor

ON/OFF and TOP-UP refer to the electric lighting switching systems detailed in Chapter 5.

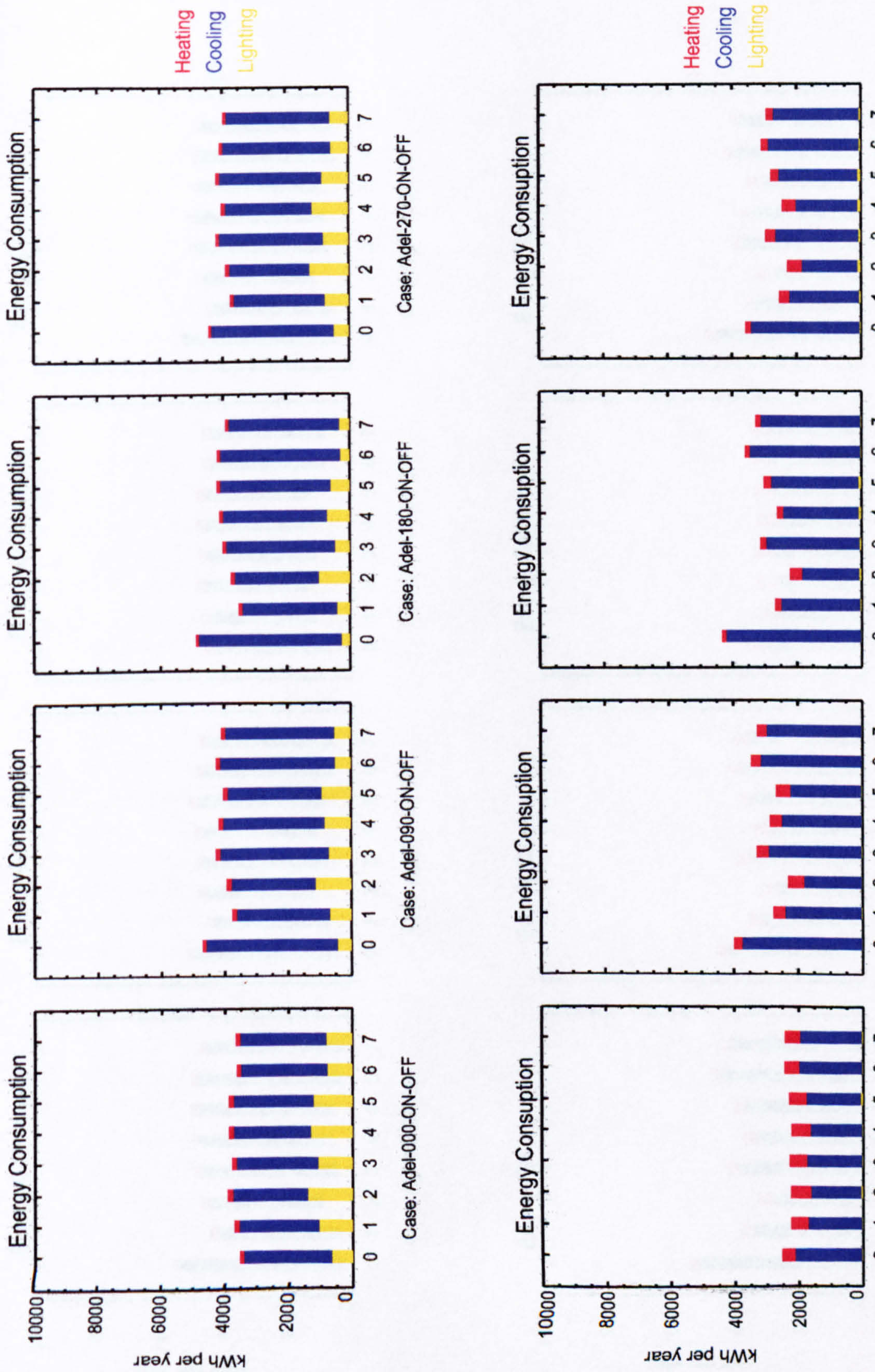

Figure B-1 Energy Consumption for Adelaide, Australia.

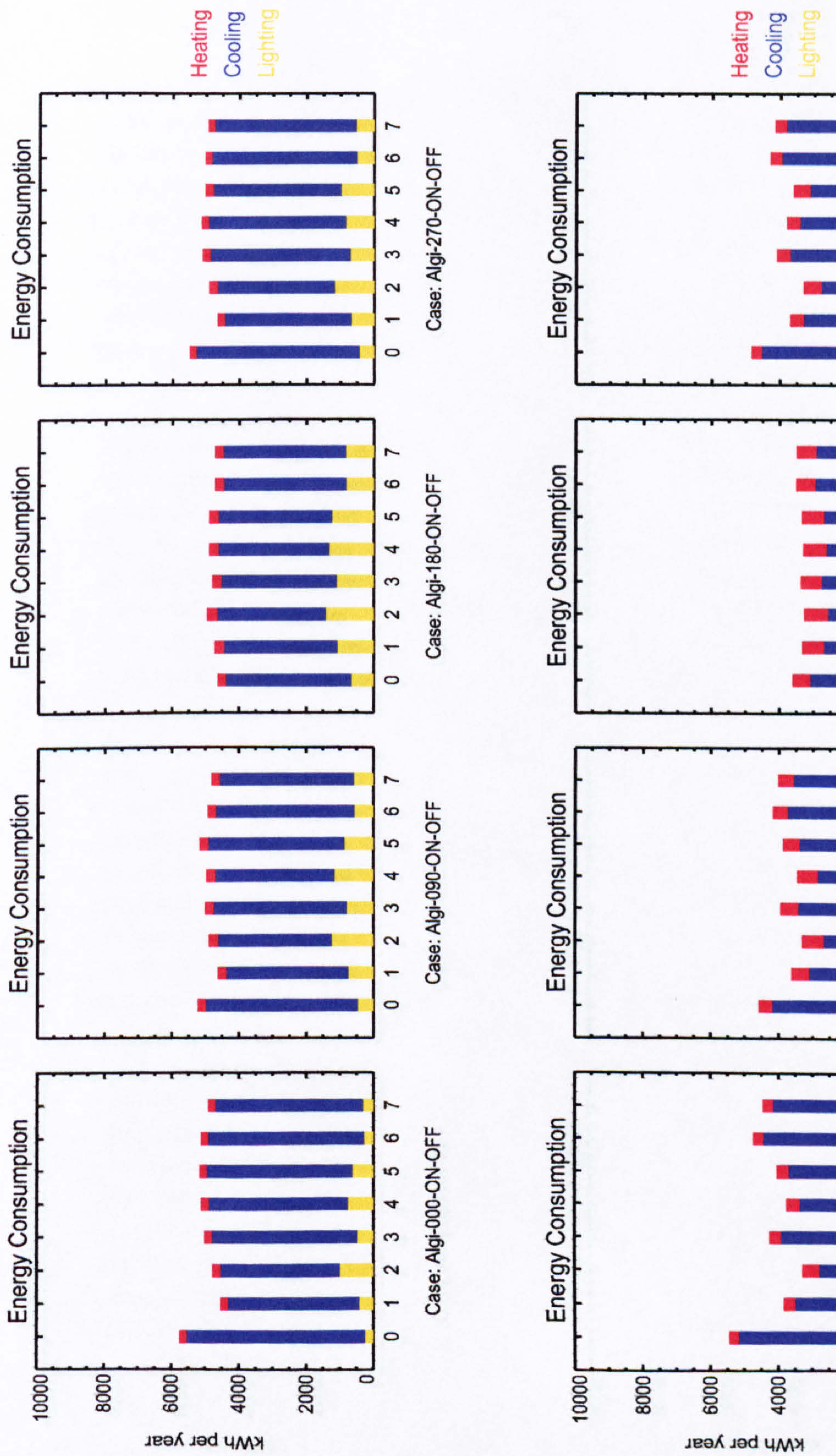

Figure B-2 Energy Consumption for Algiers, Algeria.

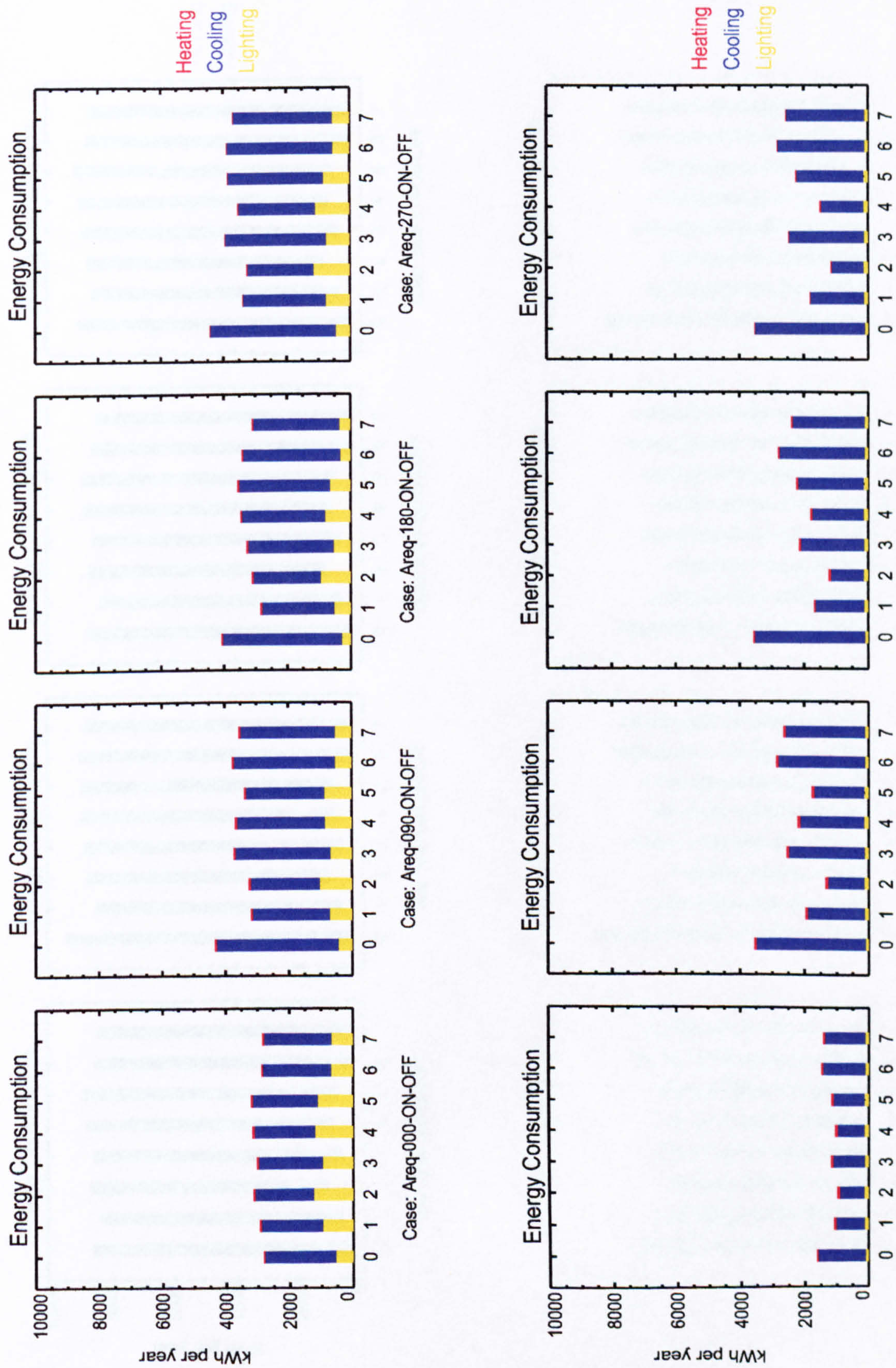

Figure B-3 Energy Consumption for Arequipa, Peru.

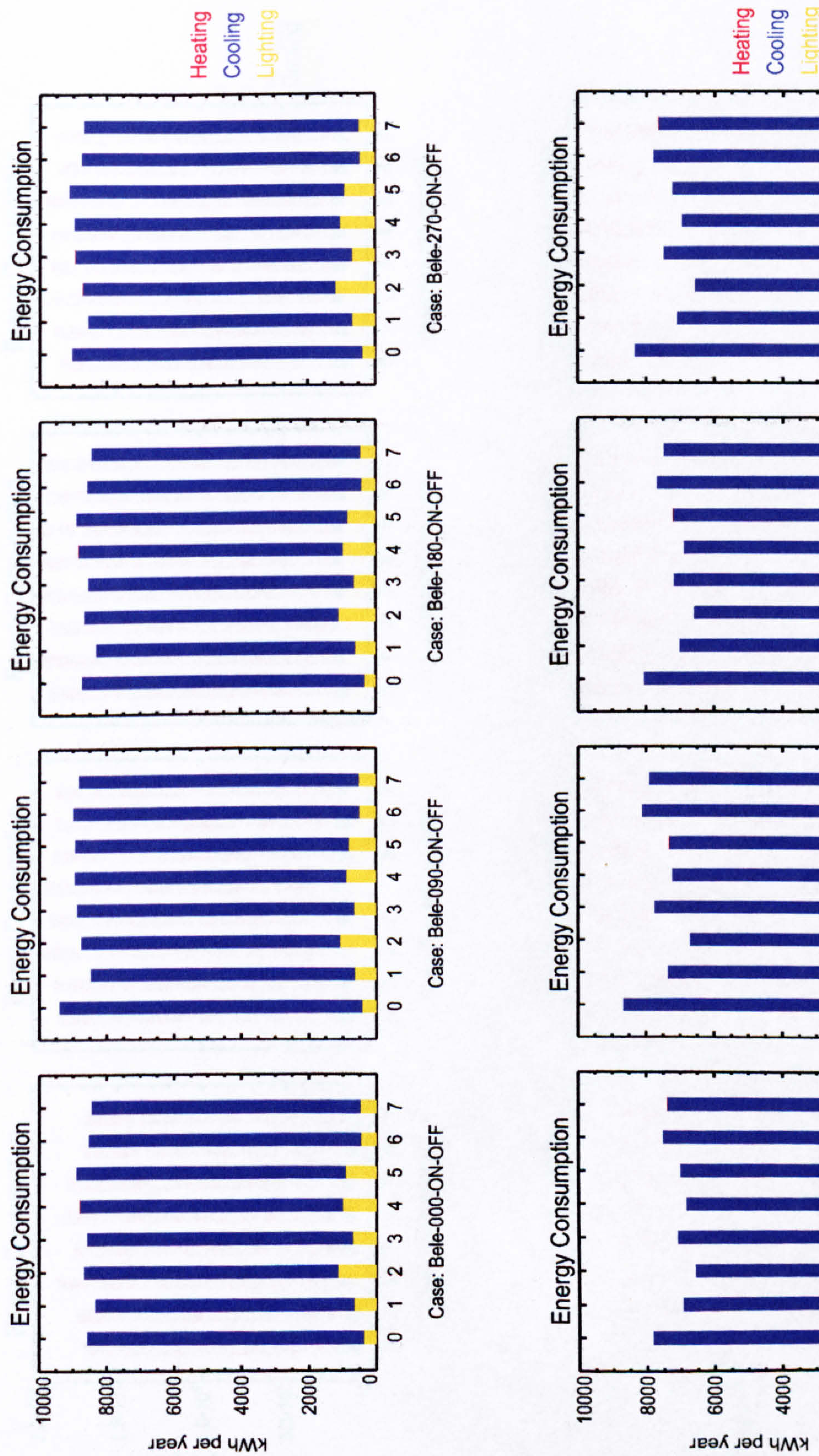

Figure B-4 Energy Consumption for Belem, Brazil.

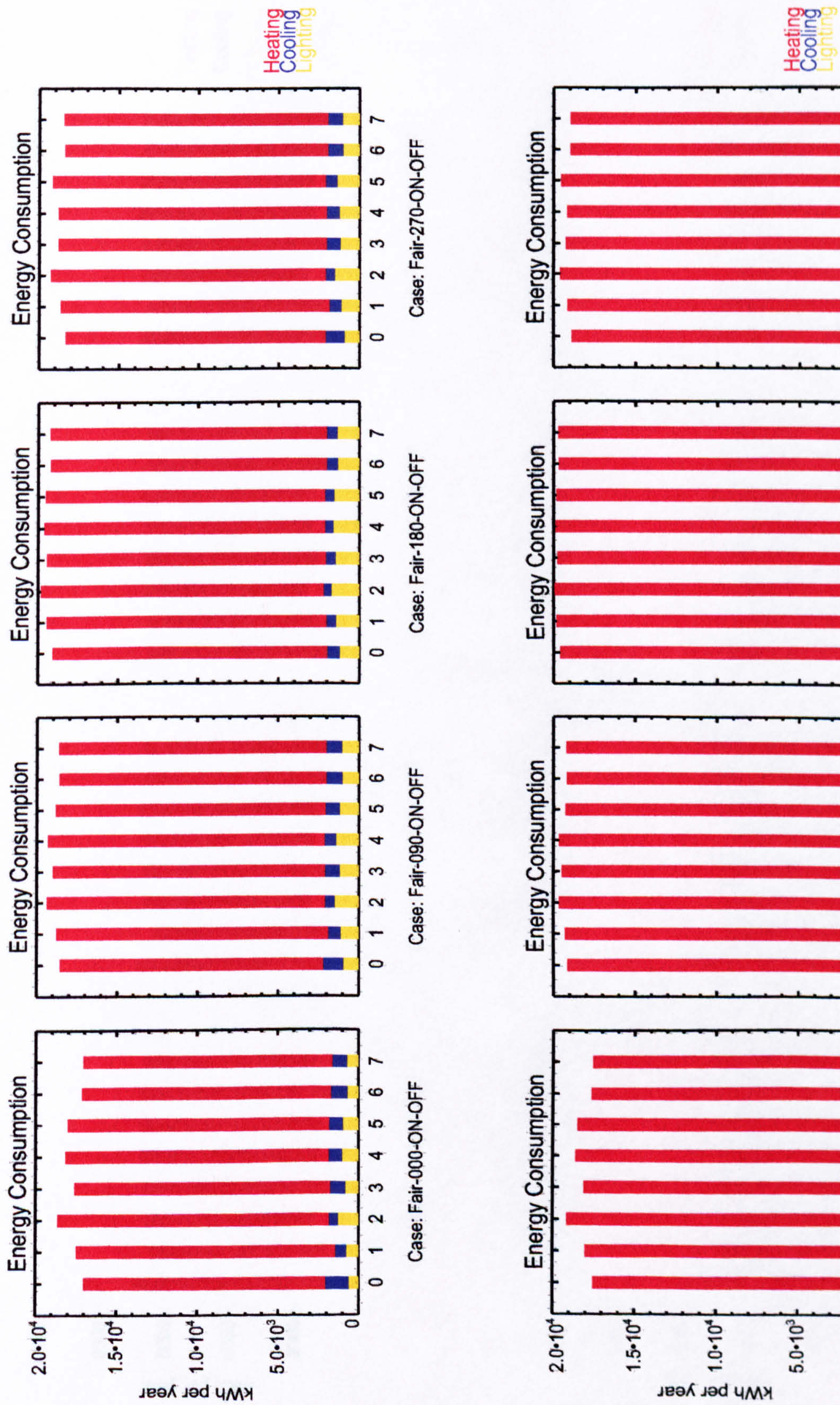

Figure B-5 Energy Consumption for Fairbanks, Alaska, U.S..

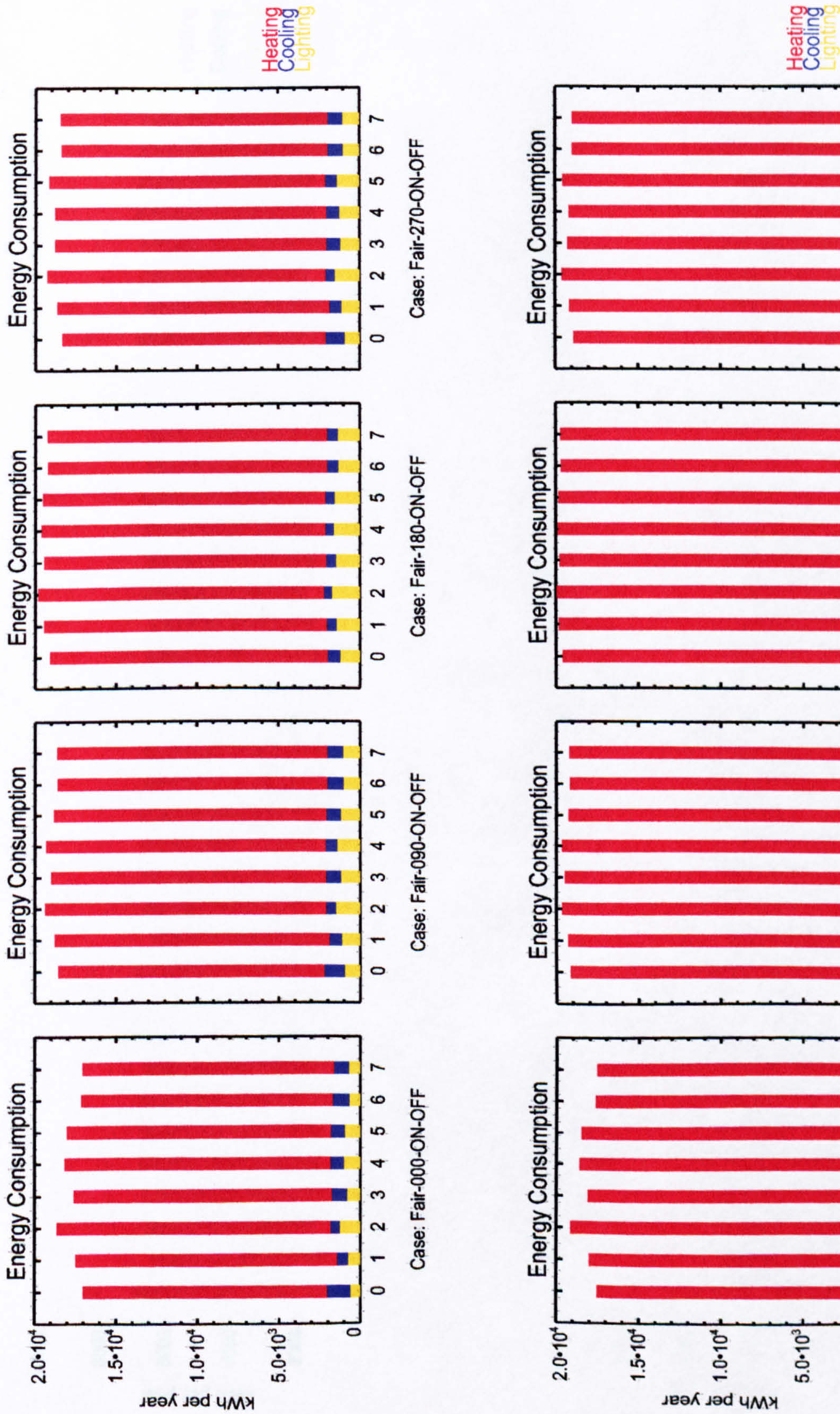

Figure B-5 Energy Consumption for Fairbanks, Alaska, U.S..

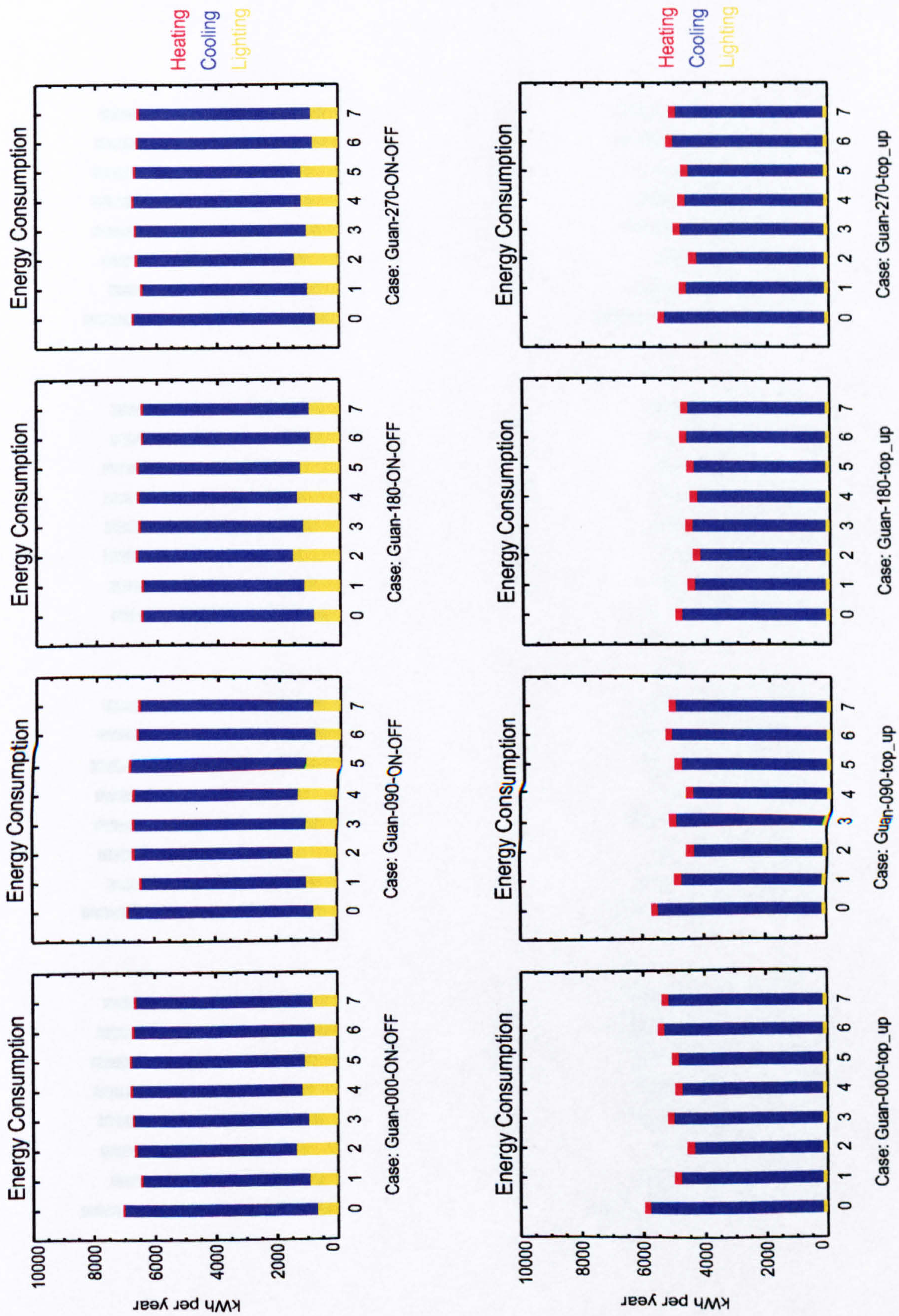

Figure B-6 Energy Consumption for Guangzhou, China.

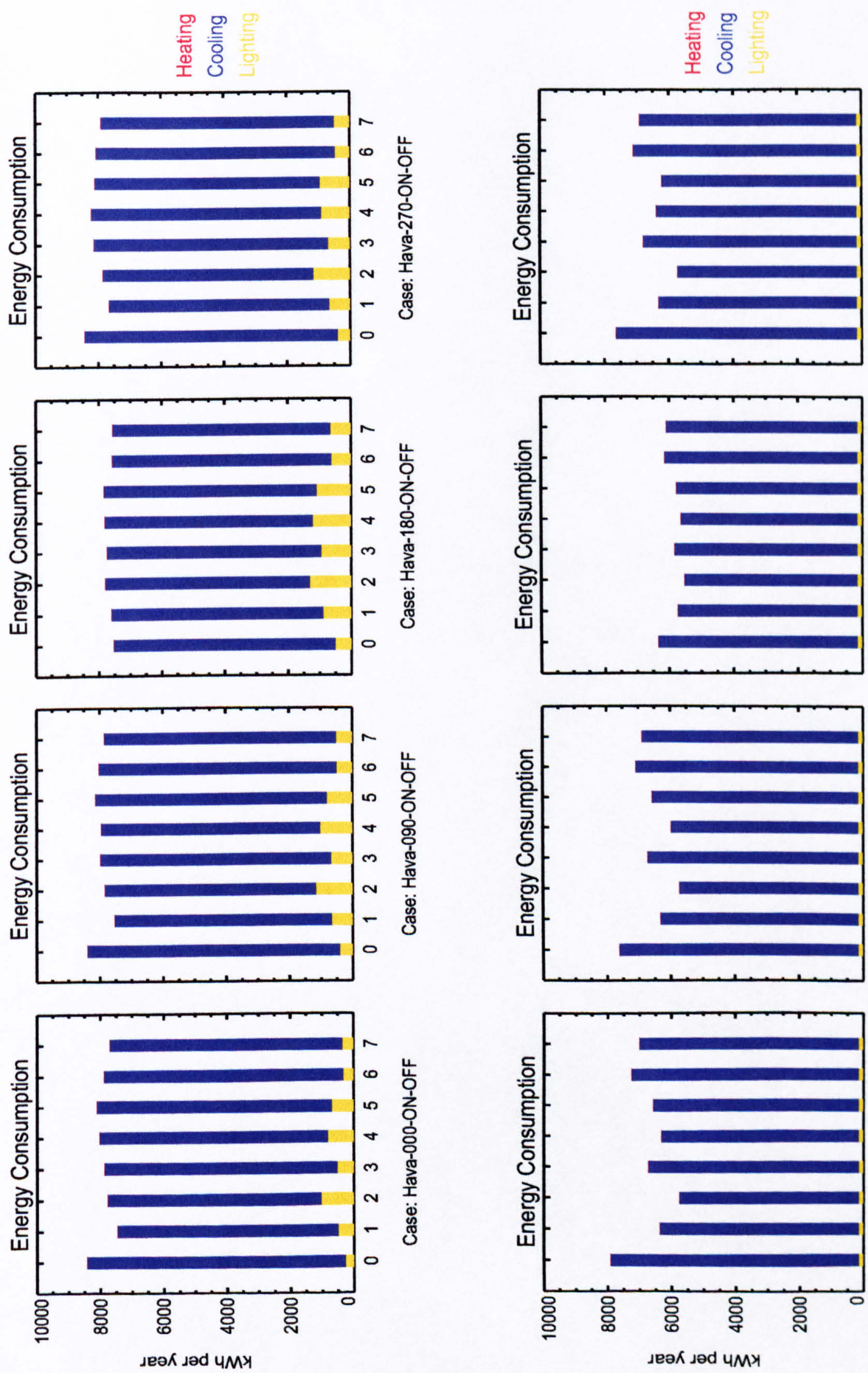

Figure B-7 Energy Consumption for Havana, Cuba.

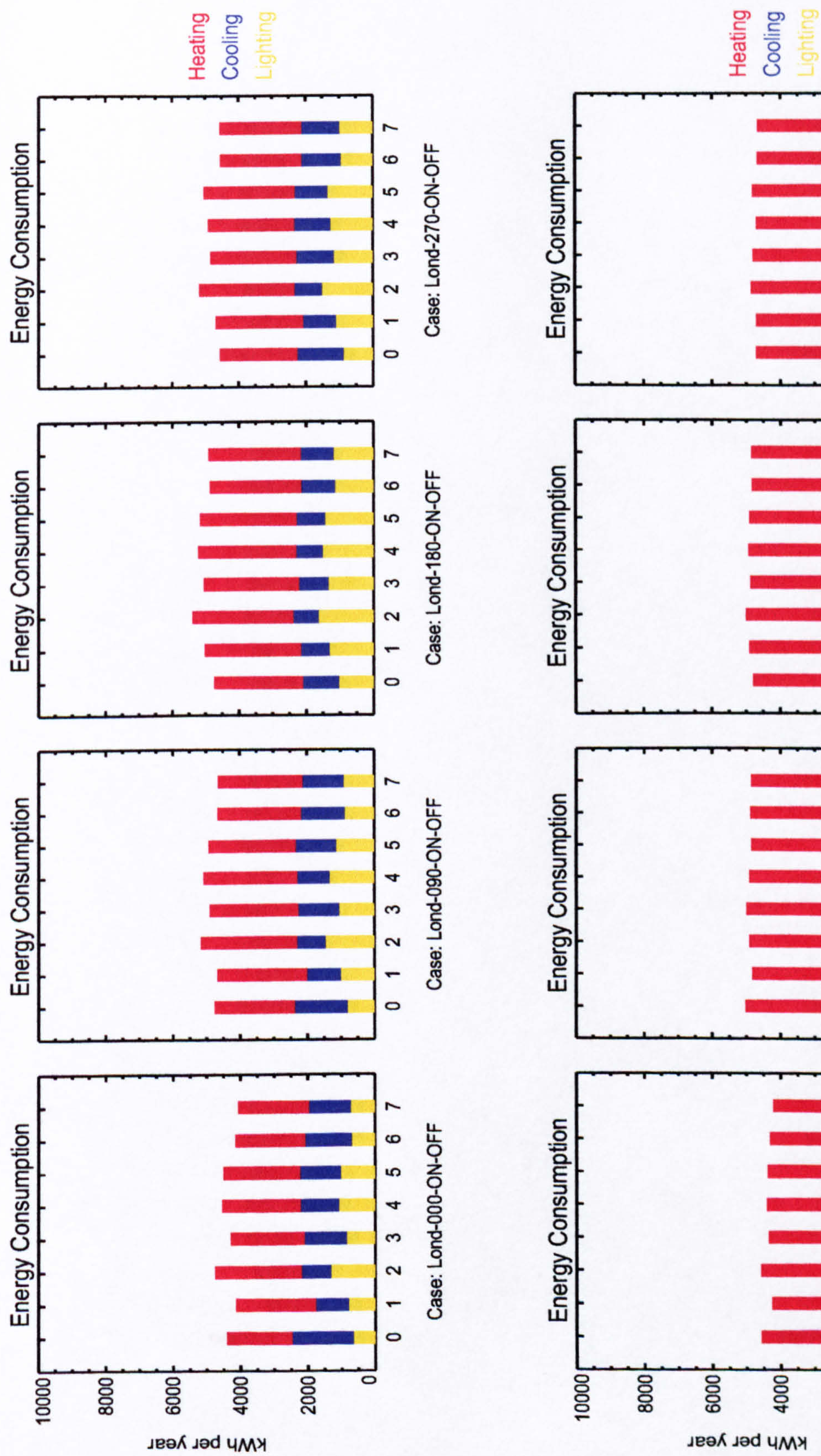

Figure B-8 Energy Consumption for London, United Kingdom.

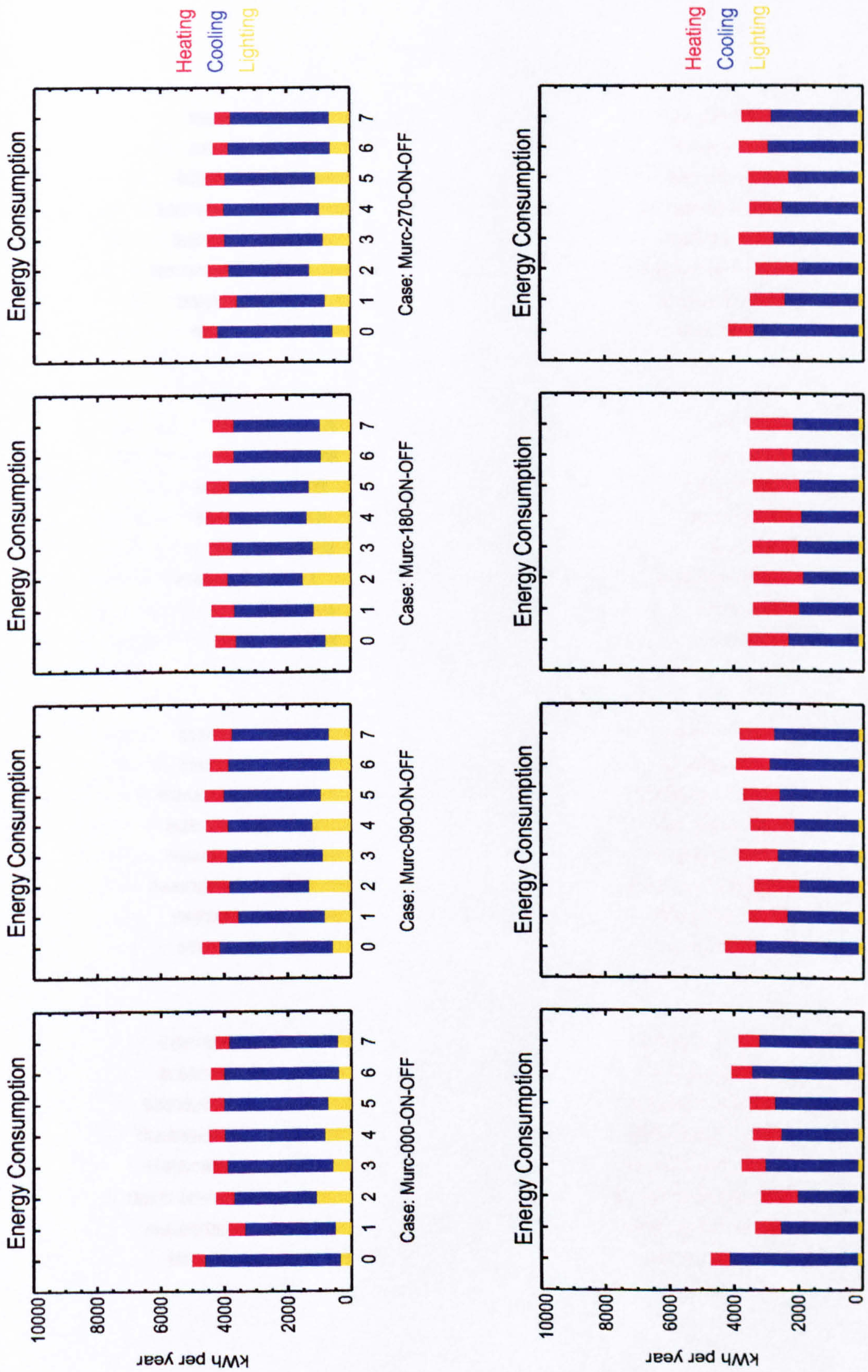

Figure B-9 Energy Consumption for Murcia, Spain.

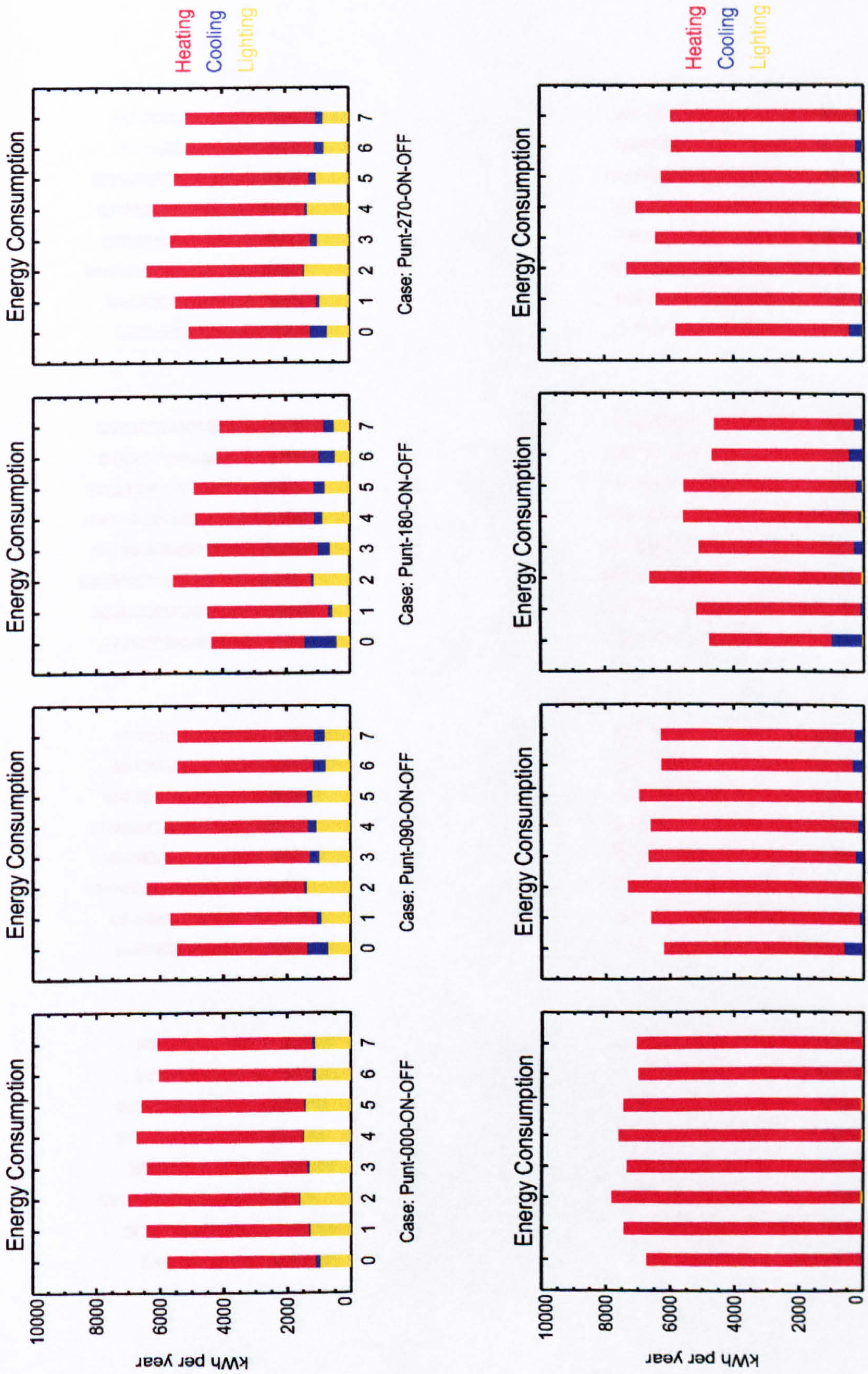

Figure B-10 Energy Consumption for Punta Arenas, Chile.

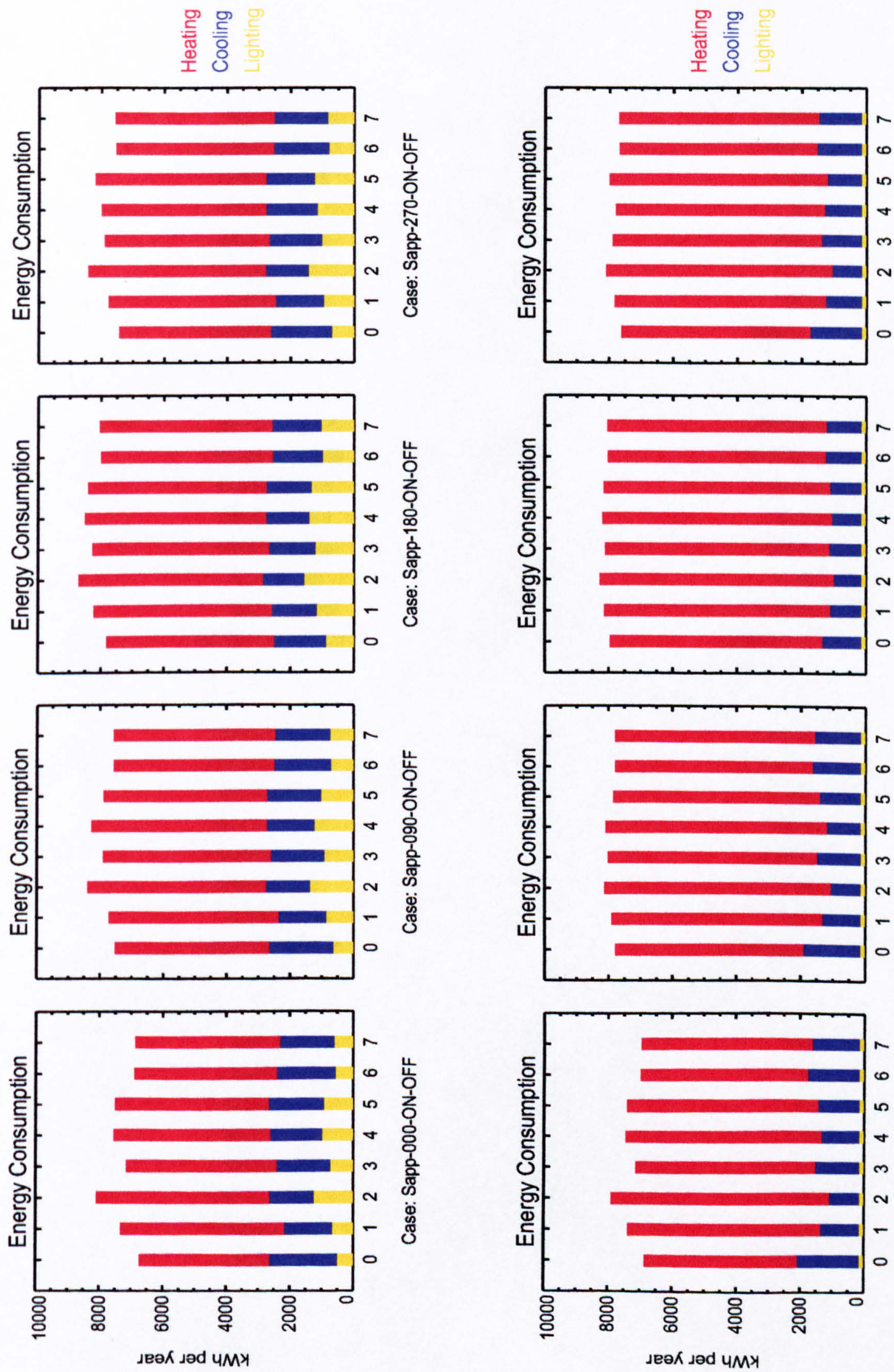

Figure B-11 Energy Consumption for Sapporo, Japan.

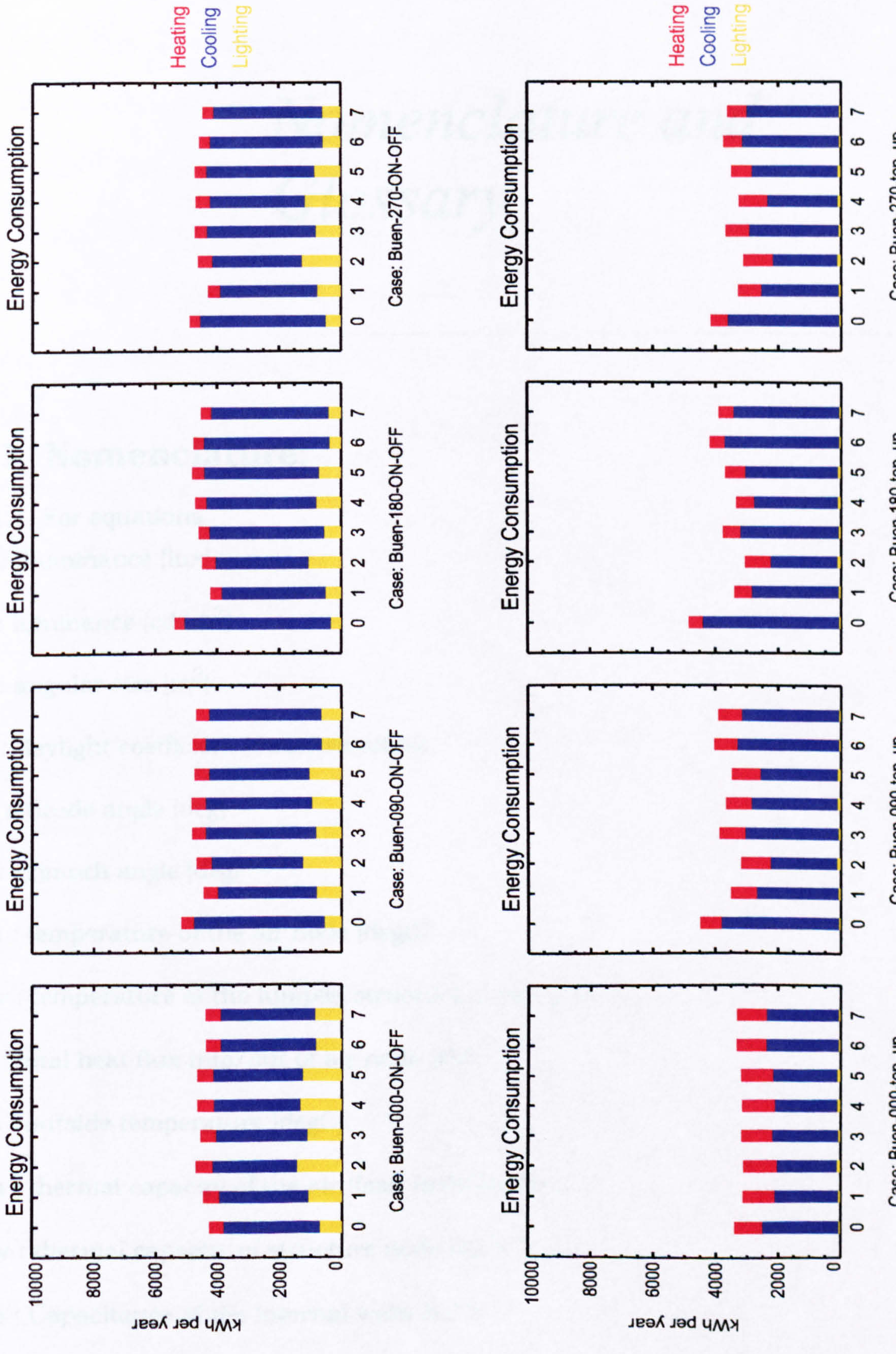

Figure B-12 Energy Consumption for Buenos Aires, Argentina.

Nomenclature and Glossary

..1 Nomenclature:

..1.1 For equations

E : illuminance [lux]

L : luminance [cd/m^2]

S : angular size [m^2]

D : daylight coefficient [dimensionless]

γ: altitude angle [deg]

α : azimuth angle [deg]

Ta : temperature of the air node [degC]

Tw : temperature of the lumped structural node [degC]

Q : total heat flux into/out of air node [kW]

To : outside temperature [degC]

Ca : thermal capacity of the air (fast) node [kJ K^{-1}]

Cw : thermal capacity of structure node [kJ K^{-1}]

Cp : Capacitance of the internal walls [kJ K^{-}]

Kf : fast conductance [kJ K^{-}]

Ki : air to structure conductance [kJ K^{-}]

Ko : structure to outside conductance [kJ K^{-}]

A : Area of the element [m^2]

V : Volume of air inside the room [m^3]

U : Overall heat transfer coefficient of the glass W/m^2 °C

N : Number of air changes per hour [units h^{-1}]

Maximum cooling capacity of HVAC plant [-kW]

Maximum heating capacity of HVAC plant [kW]

Cooling set point [deg °C]

Heating set point [deg °C]

Throttling range [deg °C]

..1.2 For the identification of cases analised using UDI concept the following nomenclature has been used:

Shading types references:

b000 : Unshaded window

h000 : Horizontal louvres tilted 0 degrees.

h045: Horizontal louvres tilted 45 degrees.

v000:Vertical louvres tilted 0 degrees

vp45:Vertical louvres tilted 45 degrees to the right.

vm45: Vertical louvres tilted 45 degreesto the left.

l000: Light-shelf at 1.35 m. from the floor

l001: Light-shelf at 1.60 m. from the floor

Climates references:

Adel : Adelaide

Algi : Algiers

Areq: Arequipa

Bele: Belem

Buen: Buenos Aires

Fair: Fairbanks

Guan: Guangzhou

Hava: Havana

Lond: London

Murc: Murcia

Punt: Punta Arenas

Sapp: Sapporo

Orientations references:

000 : South

090 : West

180 : North

270 : East

..2 Glossary

Air-balance- Air balance refers to the energy balance on an air node. The only method of heat transfer to an air node is via convection (e.g. from surfaces, ventilation casual gains or from heating).

Air-flow- Air flow is the movement of air within or between zones and can be quantified as:

ACH (air changes per hour) with respect to the volume of a zone;

A mass flow network entailing a more detailed analysis with defined components of flow rate and direction within and between zones; and

A CFD (computational fluid dynamics) network of even higher resolution within zones where they are split into many nodes, pressures and momentums.

ACH -Air Changes per Hour - unit used for quantifying default infiltration and ventilation rates, as well as a reporting unit of the mass flow analysis.

Air node capacitance- the mass of the air in the room multiplied by the specific heat of the air

Air to structure node conductance- heat flux between the air in a room and the external wall

Air to internal wall node conductance-heat flux between the air in a room and the internal walls or partitions.

Base case model - computer model of a particular building . The base case model can be used to assess the relative performance of a certain feature of the building by changing the model parameters associated withthat feature. Comparison of the results for the base case model with thise for the change model will reveal the relative performance of the feature.

Building envelope -the total area of the boundary surfaces of a building through which heat, light , air moisture are transferred between the internal spaces and the outside environment.

Boundary condition These are the temperature, flux and other environmental conditions that pertain on either side of a surface. According to the particular surface, they may be obtained from the climate data file, from the calculated values in an adjacent zone, or from user-specified values.

Capacitance of the internal walls- the mass of the internal walls multiplied by the specific heat of the material

Climate -prevalent and predictable meteorological conditions of a geografical area ; determined air temperature, solar radiation, humidity wind parameters , clouding and precipitation data for the surroundign gegraphic region #

Comfort -measure of human acceptability of the physical environment

Comfort in buildings -perceived acceptability of the physical environment

Composite construction -This refers to a type of database and its contents which are made of one or more layers of primitive materials. A composite construction may be opaque or transparent. In the latter case additional information on its optical properties is incorporated. connection

Cooling -the transfer of energy from a body of solid , liquid or gas by the existence of a temperature gradient from that body to its surroundings which are at a lower temperature, and may also be solid, liquid or gas.

Cooling set point - defines the ideal temperature (i.e., the setting of the cooling thermostat) in the space when cooling is required.

Database -a structured collection of data. This usually arranged in a series of files with the access to the database controlled by a computer program (database management system)

Energy consumption -this represents running costs which can be broken down to indicate the principal causal factors. for example the electrical power savings which result from enhanced daylight utilisation can sitgnificantly outweigh the higher heating energy consumption.

Fast conductance- flux of heat (energy per unit time) divided by a temperature gradient (temperature difference per unit lenght) , fast refers a elements like air (infiltration) or a window glass which cannot offer resistance to the flux.

Heating -the transfer of energy to a space or to the air by the existence of a temperature gradient betweeen the source and the space or air.

Heating set point - defines the ideal (i.e. the setting of the heating thermostat) in the space when heating is required.

H V A C- An abbreviation for Heat, Ventilation, and Air Conditioning

Infiltration - the movement of air from the outside (ambient) to the inside through cracks in the building envelope.

Louvre or louver- A vented opening into the home that has a series of horizontal slats and arranged to permit ventilation but to exclude rain, snow, light, insects, or other living creatures.

Maximum cooling capacity of HVAC plant - the maximum cooling power of a central air conditioning plant.

Maximum heating capacity of HVAC plant - the maximum heating power of a boiler in a central heating system.

Obstruction obstacles such as the other buildings and trees that can prevent direct insolation depending upon the time of the day.

Overhang- Outward projecting eave-soffit area of a roof; the part of the roof that hangs out or over the outside wall.

Reflectance/ reflectivity -the fraction of radiant energy incident upon it which is reflected

Structure node capacitance: the mass of the external wall in the room multiplied by the specific heat of its components.

Structure node to outside conductance: heat flux between the external wall in a room and the the air outside

Thermal comfort - generally defined as that condition of mind which expresses satisfaction withthe thermal environment (ISO 1984)

Volume of air inside the room - the measure of volume of air that the plant (either cooling or heating) process when providing

Throttling range - the temperature range over which a heating system is heating a space or a cooling system is cooling a space. For example, if the set-point for heating is 19C and the throttling range is 1C, then the system will start heating when the temperature drops to 18.5 C and continue to heat until reaches 19.5C.